BECKWITH ELECTRIC

VOLTAGE REGULATION OF THE DISTRIBUTION GRID

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Voltage Regulation and Power Quality Track
Monday and Tuesday Sessions

HUBBELL

SESSION 3 – LTCs, regulators, and their controls

Regulators are Series Devices

Regulators in General:

1. Uni-Directional – They can only change the voltage on the load-side of the regulator and have no effect on the source-side.

2. They can correct voltage, but they have no effect on power factor.

3. They are installed in series between the Source and Load.

4. They are a voltage source, they add or subtract voltage to the existing voltage.

5. Should be used to correct voltage drop caused by real current flow.

Regulators - How they work

Regulators Are a Voltage Source

1. A Series Winding is added.

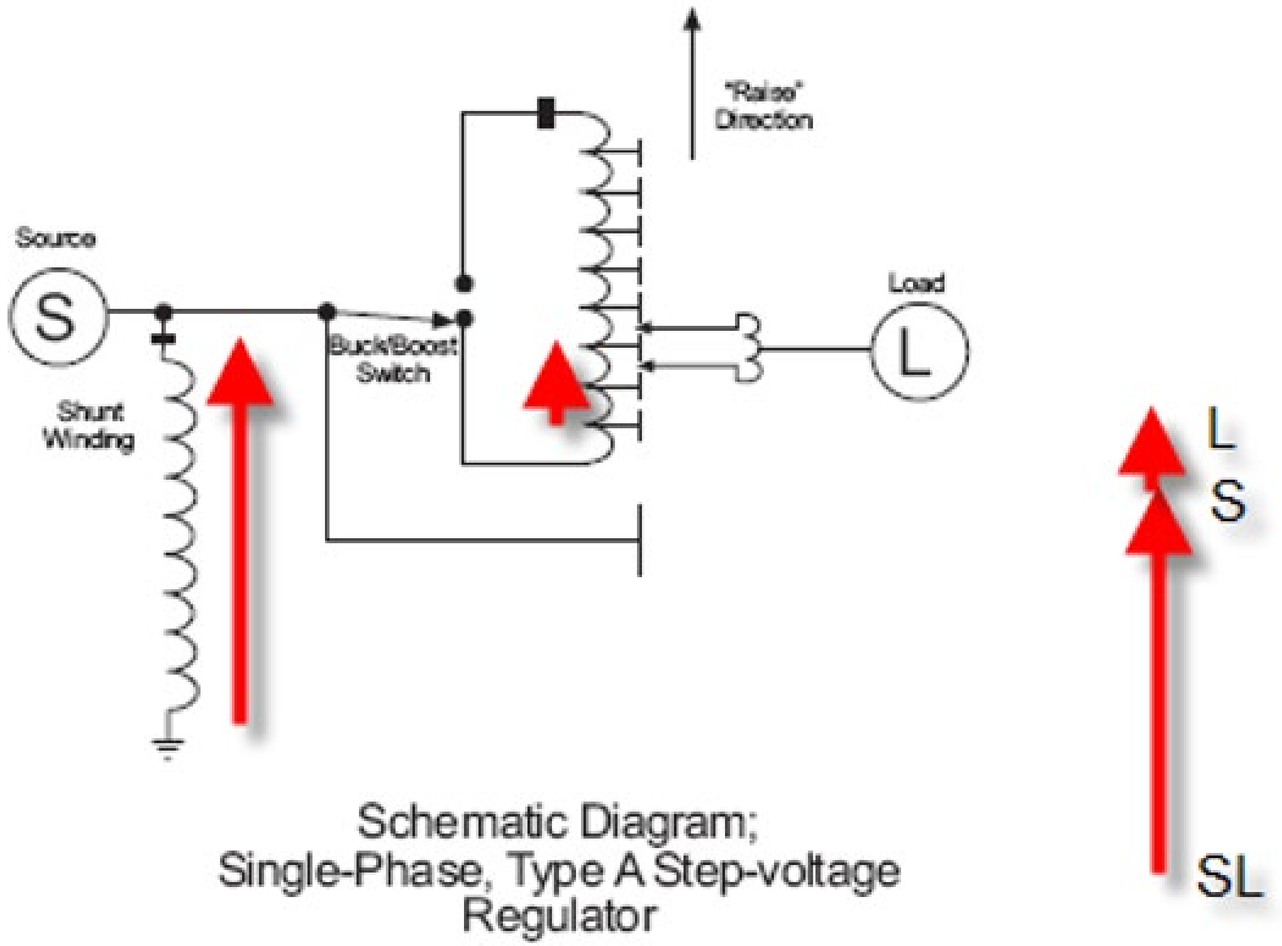
2. The Series Winding can add or subtract voltage from the incoming voltage.

3. In the Neutral Position the incoming voltage (Source) bypasses the series winding and goes directly to the outgoing (Load).

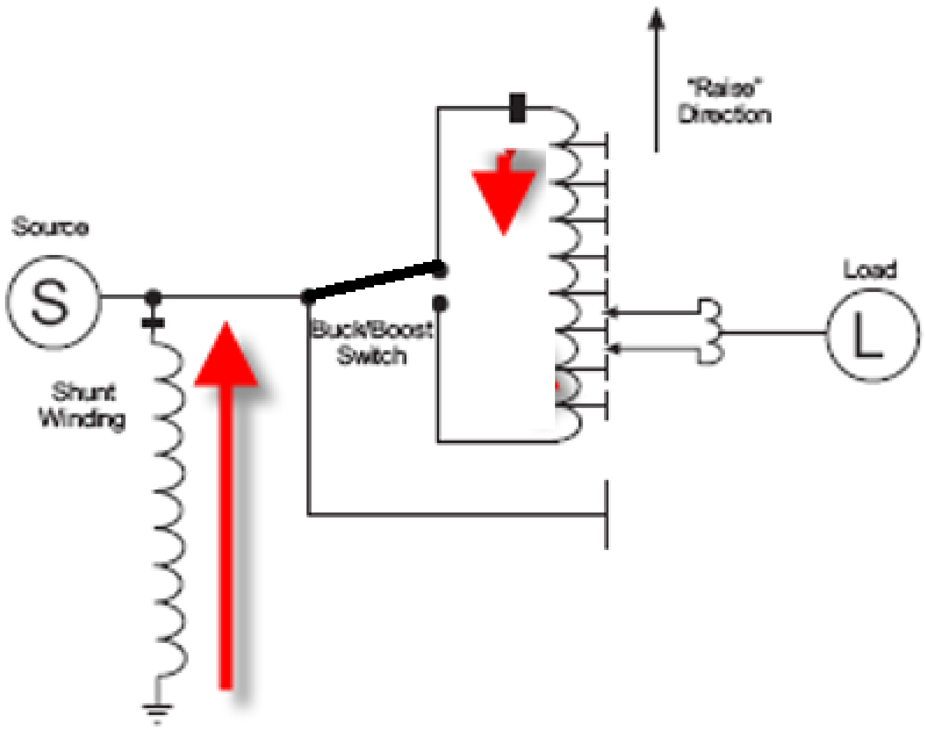
4. Regulators typically have 16 raise taps, a neutral position and 16 lower taps.

5. Regulators typically are 10% boost/buck and therefore change the voltage by 0.75 VAC on a 120 VAC basis per tap.

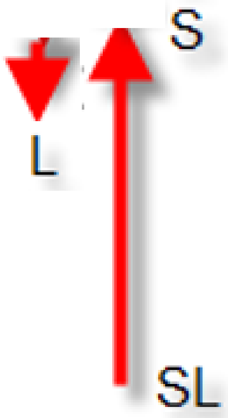
Regulator Raising the Voltage



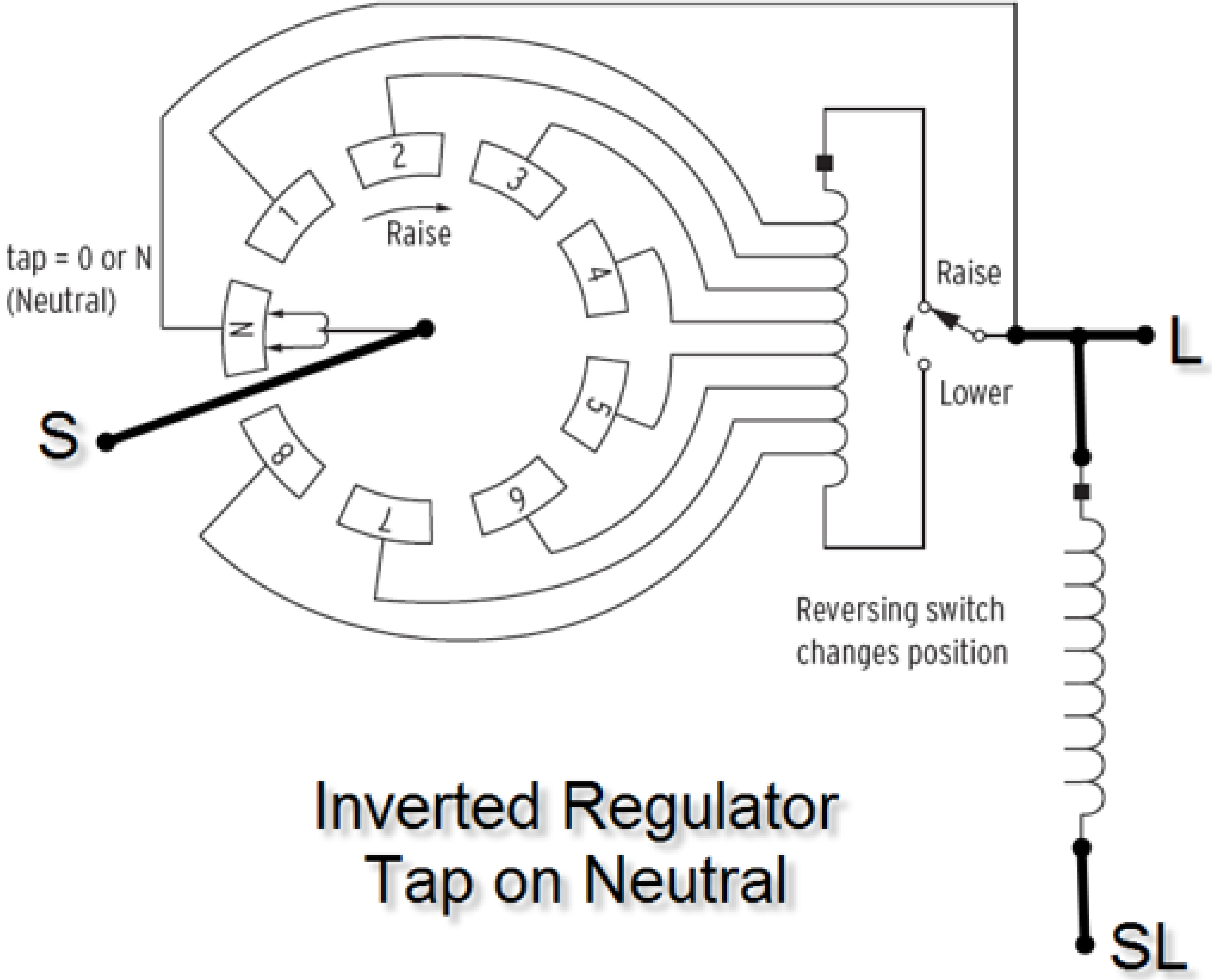
Regulator Lowering the Voltage



Schematic Diagram;
Single-Phase, Type A Step-voltage Regulator

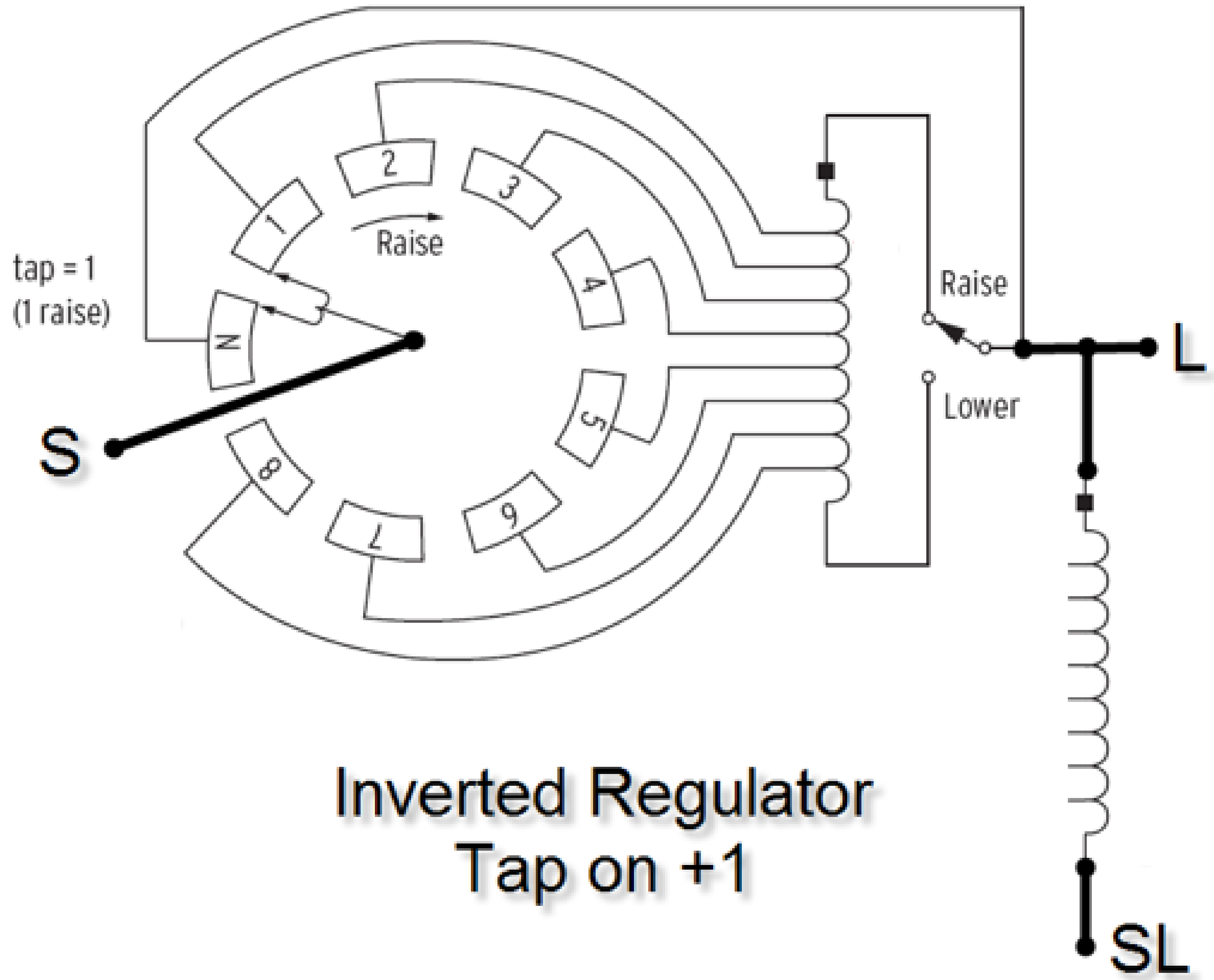


Regulator Taps



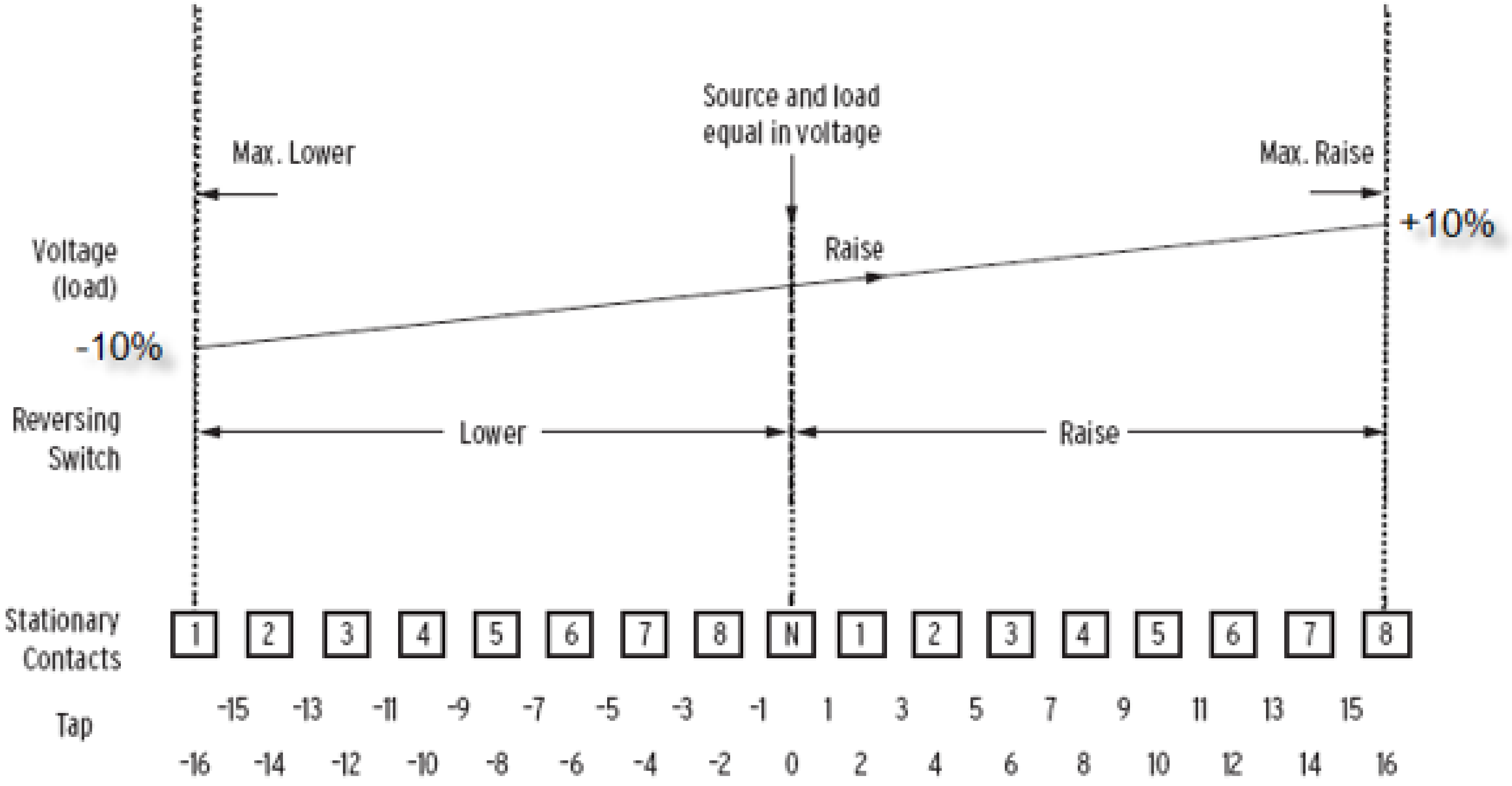
Inverted Regulator
Tap on Neutral

Regulator On 1 Raise

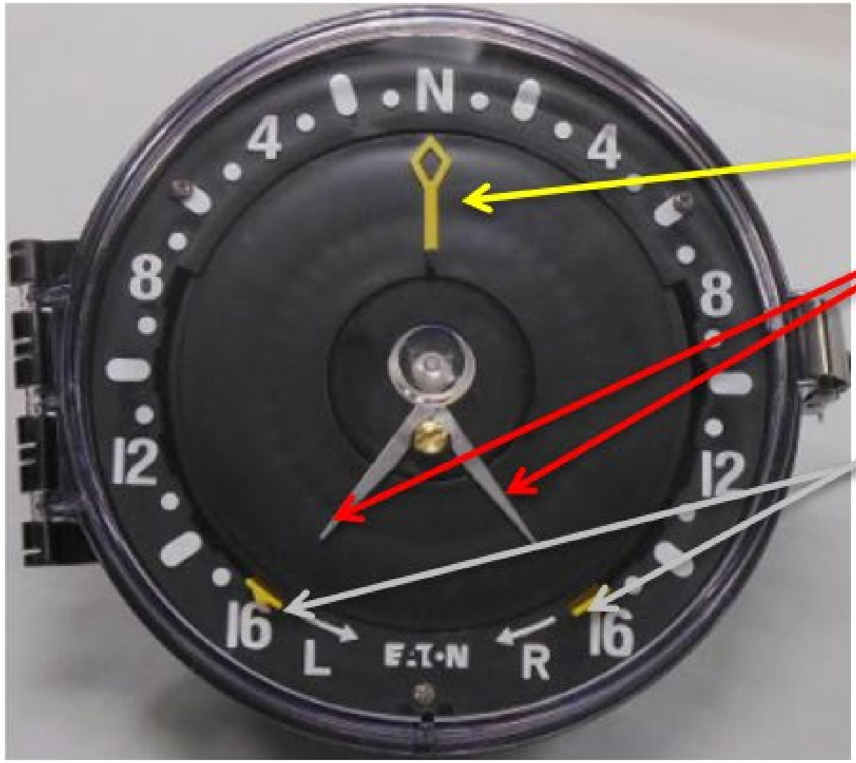


Regulator Taps

Regulators



Tap Position Indicators



Position Indicator and Drag Hands and Limit switches

1. Position Indicator shows current tap position
2. Drag Hands show the lowest and highest tap reached since last time they were reset
3. Limit switches can be moved to block tap positions

Regulator Controls

Regulator Controls

Analog Controls

Digital Controls

Regulator Sizes

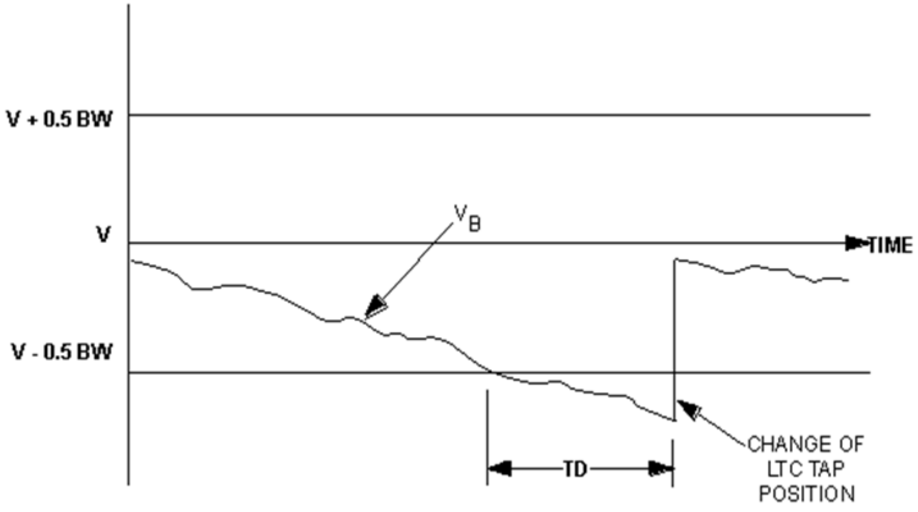
Rated Volts	Rated kVA	Load Current Ratings (Amperes)*				
		Regulation Range				
		±10%˙	±8 3/4%	±7 1/2%	±6 1/4%	±5%
6600 95 kV BIL	33	50	55	60	68	80
	66	100	110	120	135	160
	99	150	165	180	203	240
	132	200	220	240	270	320
	198	300	330	360	405	480
	264	400	440	480	540	640
	330	500	550	600	668	668
	396	600	660	668	668	668
	440	668	668	668	668	668
11000 95 kV BIL	55	50	55	60	68	80
	110	100	110	120	135	160
	165	150	165	180	203	240
	220	200	220	240	270	320
	330	300	330	360	405	480
	440	400	440	480	540	640
	550	500	550	600	668	668
	660	600	660	668	668	668
15000 150 kV BIL	75	50	55	60	68	80
	150	100	110	120	135	160
	225	150	165	180	203	240
	300	200	220	240	270	320
	450	300	330	360	405	480
	600	400	440	480	540	640
	750	500	550	600	668	668
16000 150 kV BIL	160	100	110	120	135	160
	320	200	220	240	270	320
	480	300	330	360	405	480
22000 150 kV BIL	110	50	55	60	68	80
	220	100	110	120	135	160
	330	150	165	180	203	240
	440	200	220	240	270	320
	660	300	330	360	405	480
	880	400	440	480	540	640
	999**	454	454	454	454	454
33000 200 kV BIL	165	50	55	60	68	80
	330	100	110	120	135	160
	495	150	165	180	203	240
	660	200	220	240	270	320
	825	250	275	300	337	373
35000 200 kV BIL	175	50	55	60	67.5	80
	350	100	110	120	135	160
	525	150	165	180	202.5	240
	700	200	220	240	270	320

Basic Control Settings - Band

Basics of Voltage Regulation

Minimum basic settings for a regulator control to operate are:

- Bandcenter (100~135 V in 0.1 V increments).
- Bandwidth (1~10 in 0.1 V increments).
- Time Delay (1~120 s in 1 s increments).



V=Voltage Setpoint of tapchanger control

Basic Control Settings – Time Delay

Regulator Controllers

Start with Basics – Time Delay

Time Delay has two primary functions:

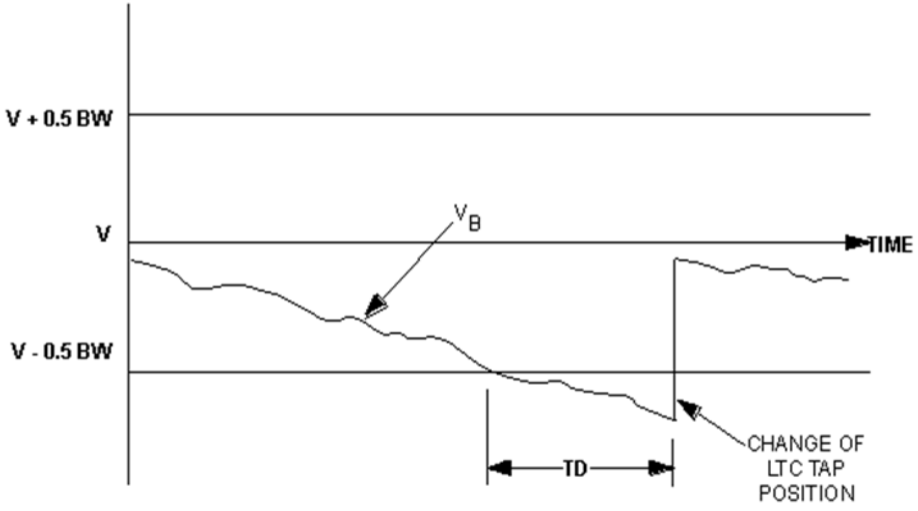
1. Delay for motor starts. Motors draw 5-7 times normal current when first starting and this causes a voltage sag but lasts only for 5-60 seconds. Without time delay the regulator will raise the voltage when the motor starts and within 60 seconds have to lower back once the motor is up to full speed.

2. Coordination with other devices regulating the voltage such as line regulators and switched capacitor banks.

Basic Control Settings – Time Delay

Basics of Voltage Regulation

- Two type of timers:
  - Definite Time Delay – Time delay fixed (1~120 s @ 1 s).
  - Inverse Time Delay – Time delay varies with the amount of voltage difference. The greater the difference, the less time delay.



V=Voltage Setpoint of tapchanger control

Basic Control Settings – Time Delay

Basics of Voltage Regulation

- The Inverse Time TD if enabled will determine the actual time delay depending on how far out of band the voltage is:
  - If the BW is set at 2 V for example, the control will take the full setting in seconds if voltage goes out of band by less than 1 V.
  - If voltage drops a full BW (ie 2.V) then actual time will be reduced by 50%.
  - If voltage drops 2 full BW (ie 4 V) then actual time will be 25% of setting.
- Inverse Time will allow for faster voltage recovery or reduction.

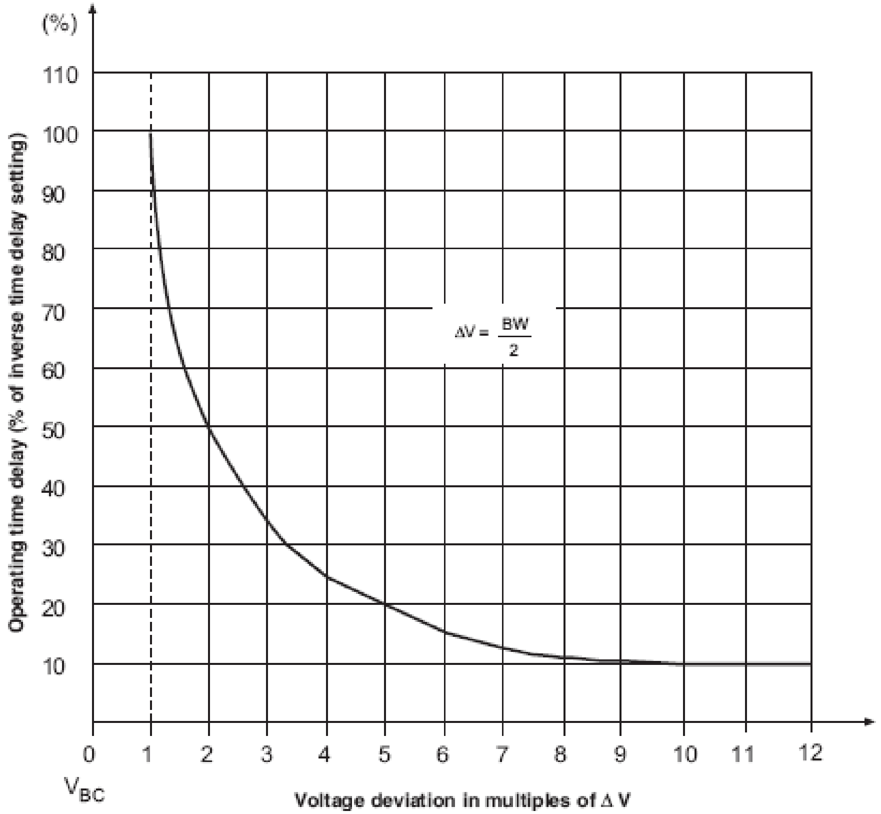
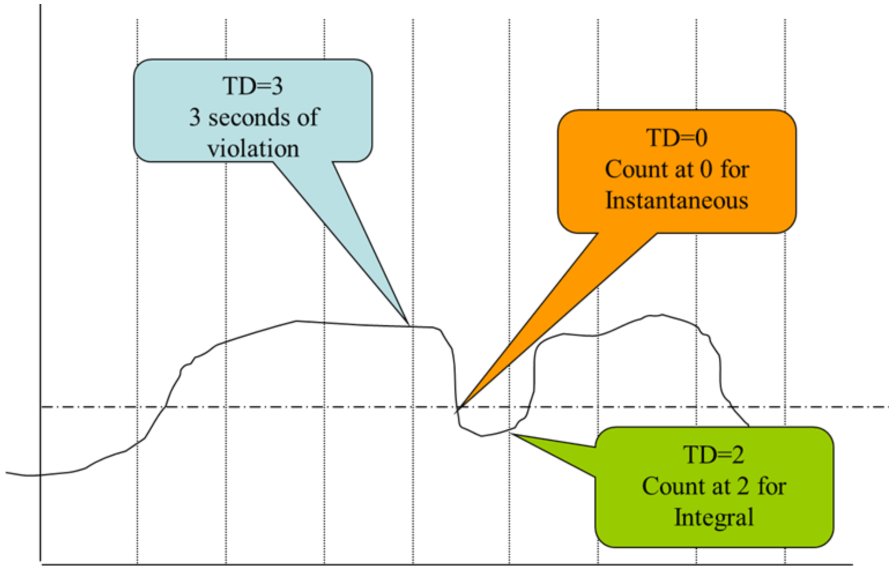


Figure 3-1 Inverse Time Delay Curve

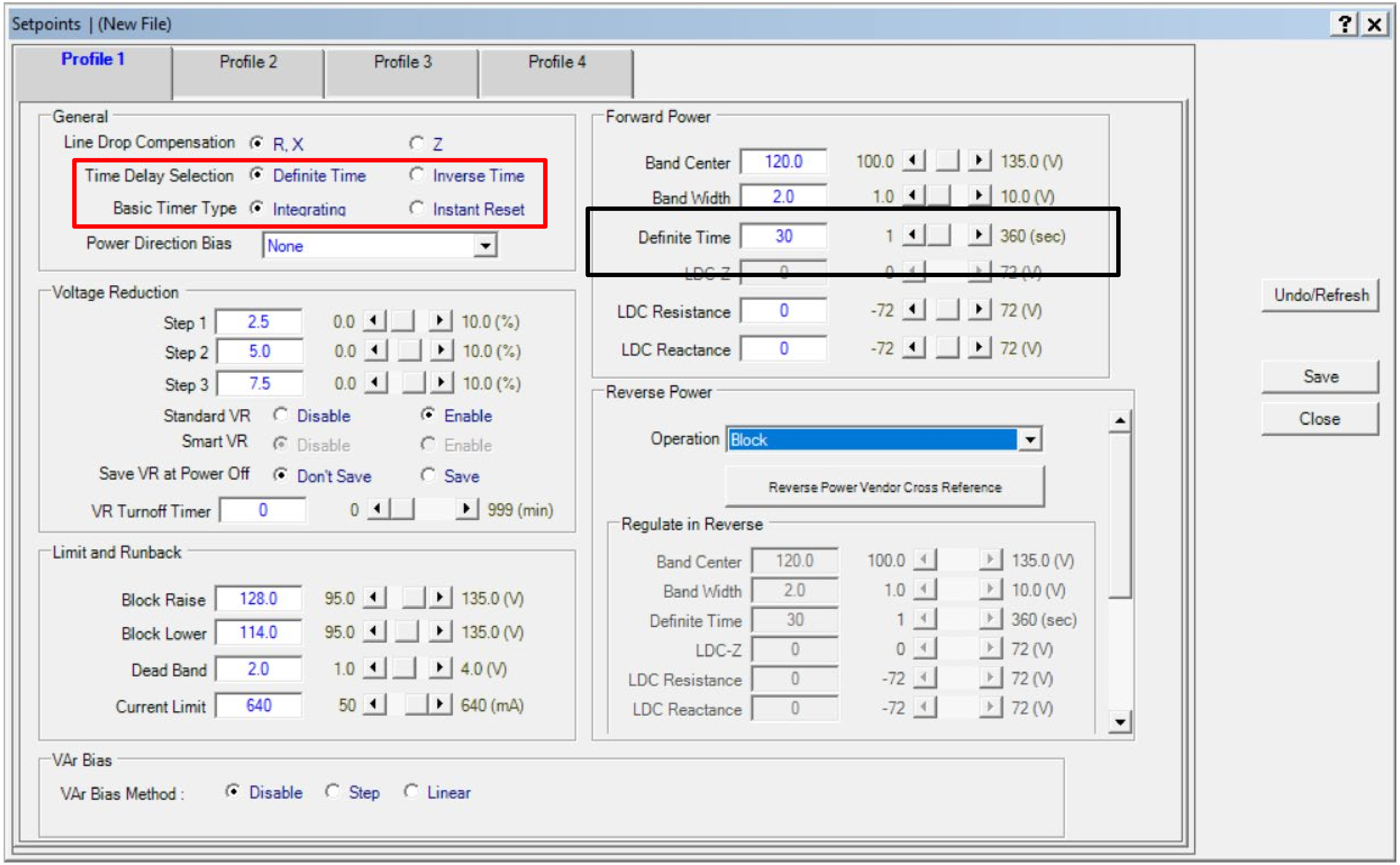
Basic Control Settings – Time Delay

Basics of Voltage Regulation

- Two types of TD Reset:
  - Instant (default).
  - Integrating.
- TD will start counting when voltage goes out of band, Instant Reset will reset the count to zero instantly when voltage returns to within the band.
- With Integrating Reset the timer will count backwards towards zero when voltage is returns to within the band.
- Integrating will increase operations but help keep a flatter voltage profile.



Basic Control Settings



Basic Control Settings – Time Delay

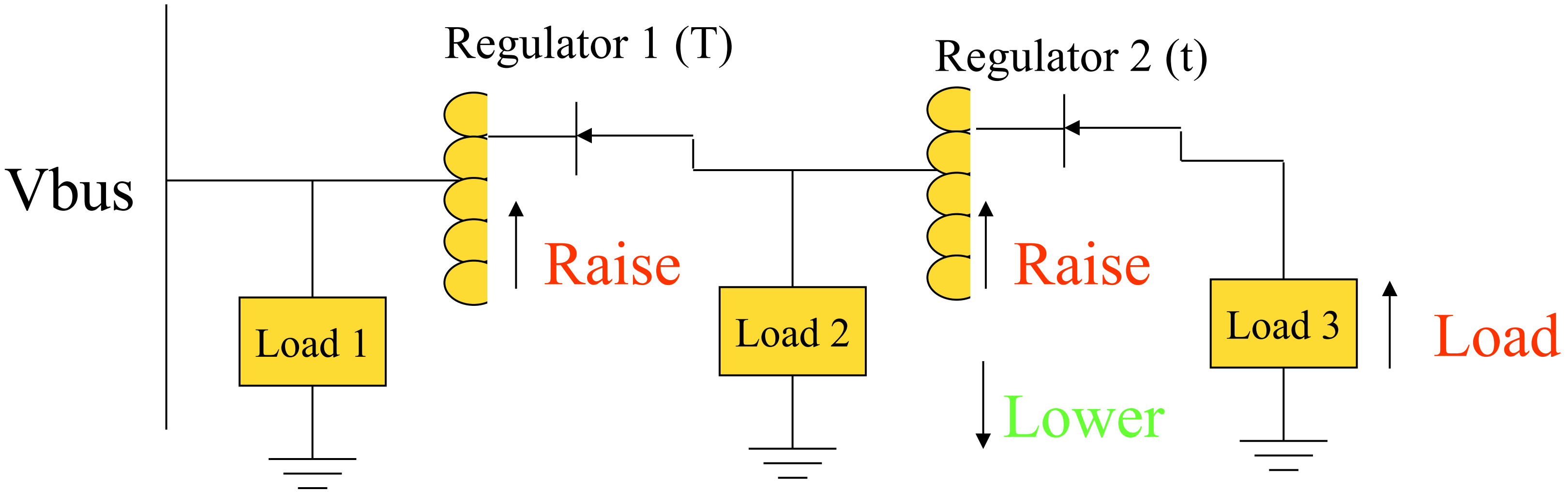
Time Coordination

- Long Feeders may require additional regulators closer to the load.
- This creates a coordination issue with Time Delay settings on each regulator.
- In order to reduce regulator operations, the regulator closest to the source should be allowed to operate first.
- It is recommended that each regulator after the closest to source have an additional 15 seconds delay to avoid hunting.

Basic Control Settings – Time Delay

Hunting

- Cascaded Regulators
  - If Regulator 2 has a time delay less than regulator 1 and Load 3 has a large increase, both regulators will be out of band - Low and will start timing.
  - R2 will time out first and take a tap to raise voltage.
  - R1 will still see a low voltage thus will continue timing and take a tap to raise voltage.
  - R2 now sees a high voltage and will take a tap to lower the voltage.
  - By not doing the proper coordination R2 took two unnecessary taps.



Basic Control Settings

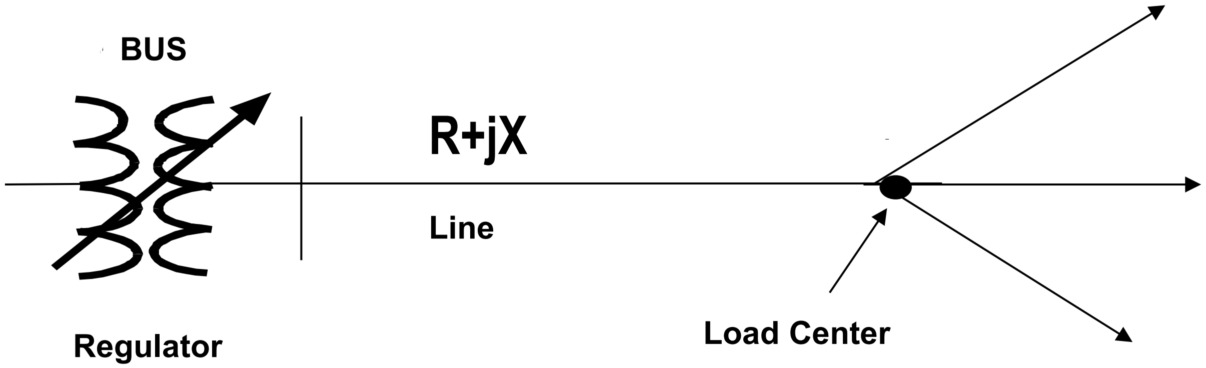
LDC is Used to Compensate for Voltage Drop

- **Voltage Drop is due to current through the resistive and reactive network of distribution system and customer loads.**
- **As current increases, voltage drop increases.**
- **Reactive current increases cause 3 – 4 times more voltage drop as majority of impedance is reactive.**
  - **Typical X/R ratios 3:1 to 6:1.**

Basic Control Settings - LDC

Line Drop Compensation (LDC)

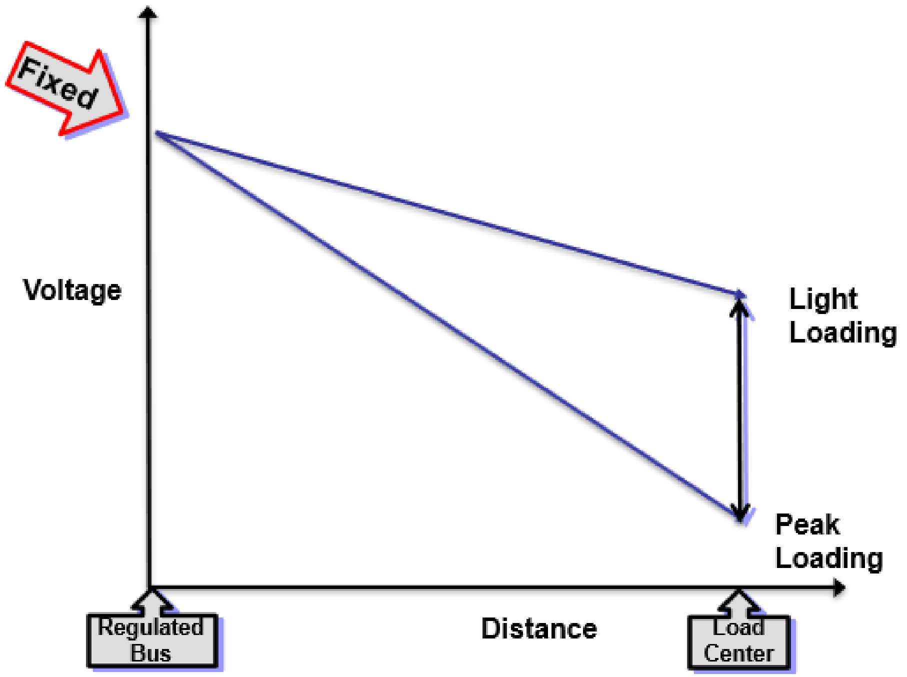
- LDC allows voltage regulation closer to the load accounting for line impedance, load and associated voltage drop
- Used to maintain voltage at a remote load center
- Two types of LDC are provided: R/X_L and Z

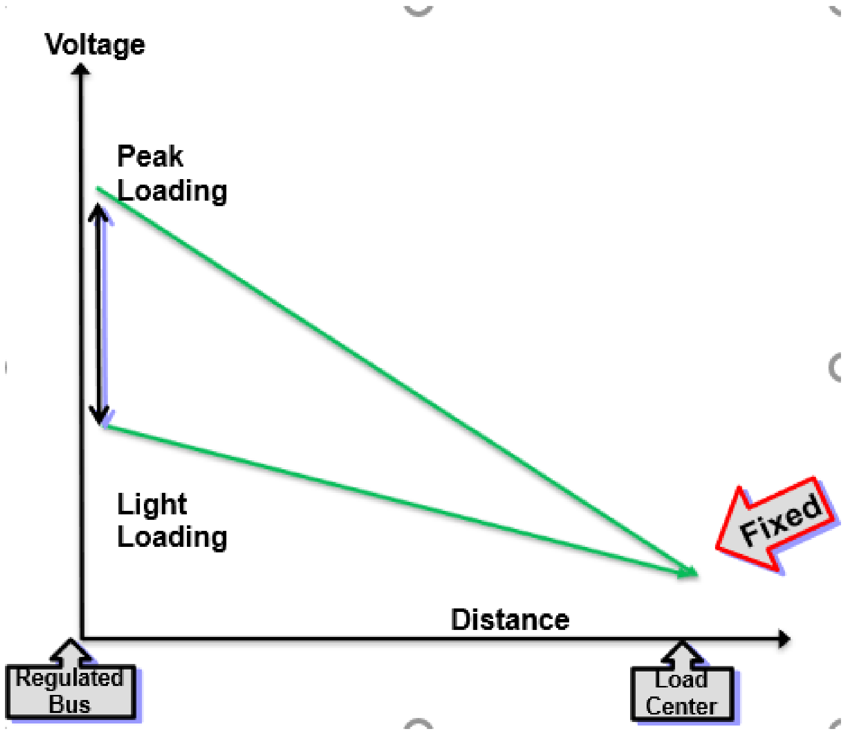


Basic Control Settings- LDC

- Without LDC the voltage is high at the front of the circuit at all times to account for the full load scenario that may cause low voltage at the end of the circuit.

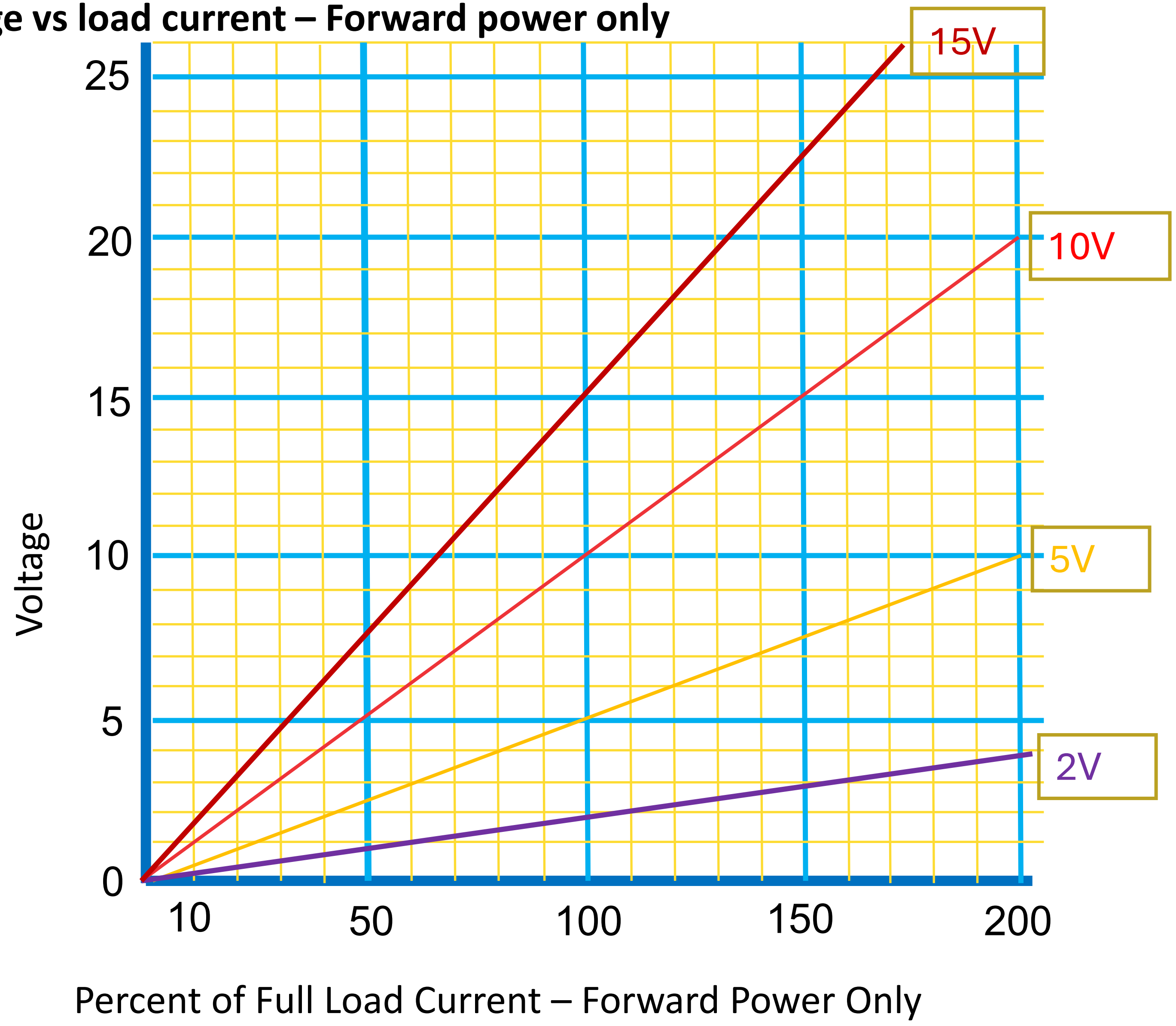
- With LDC the voltage at the front of the circuit is lower at low load levels and raises as the load increases.





Basic Control Settings - LDC

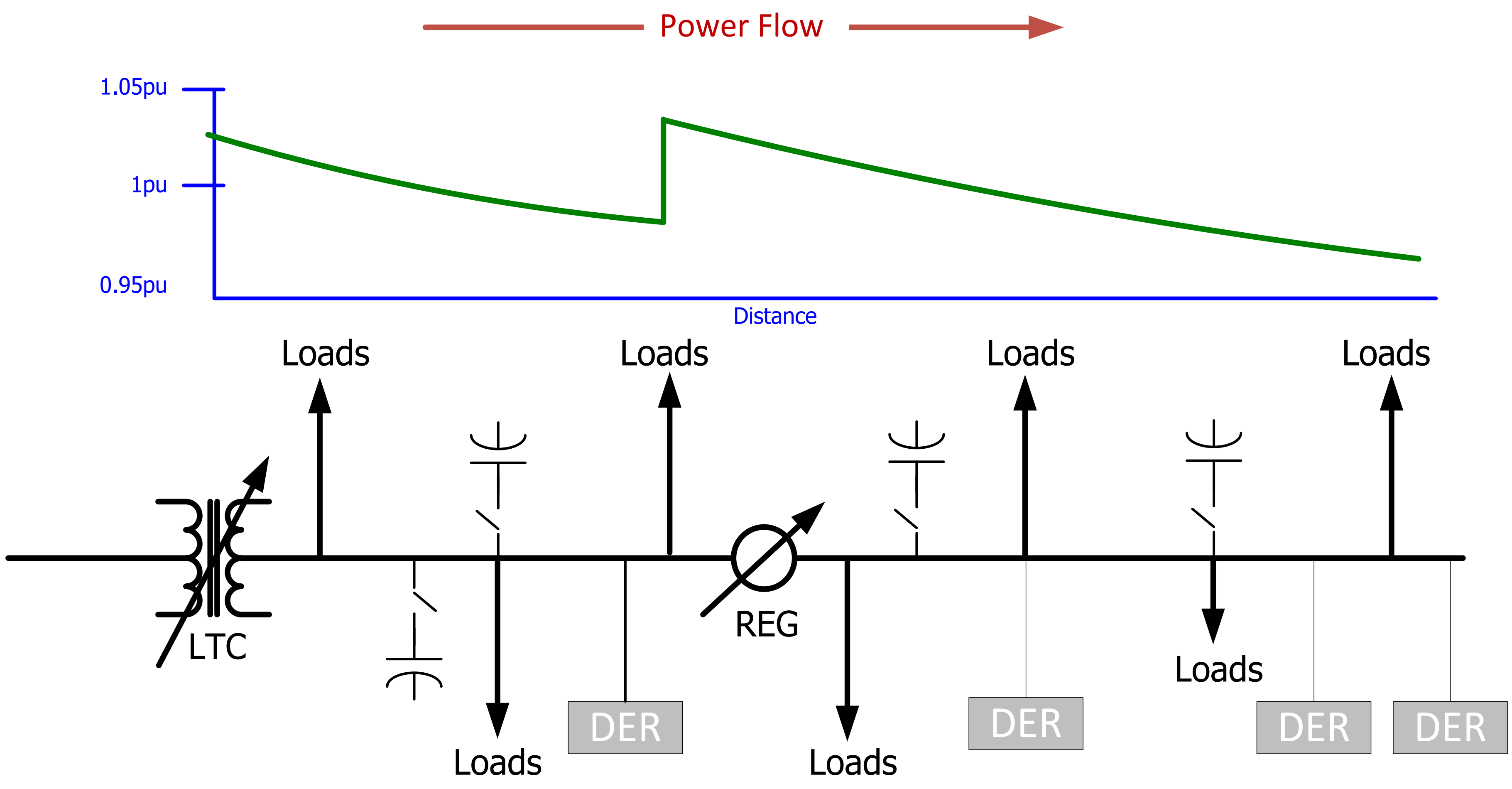
LDC voltage vs load current – Forward power only



Notice there is no cap on the compensation however the block raise setting will limit the high voltage.

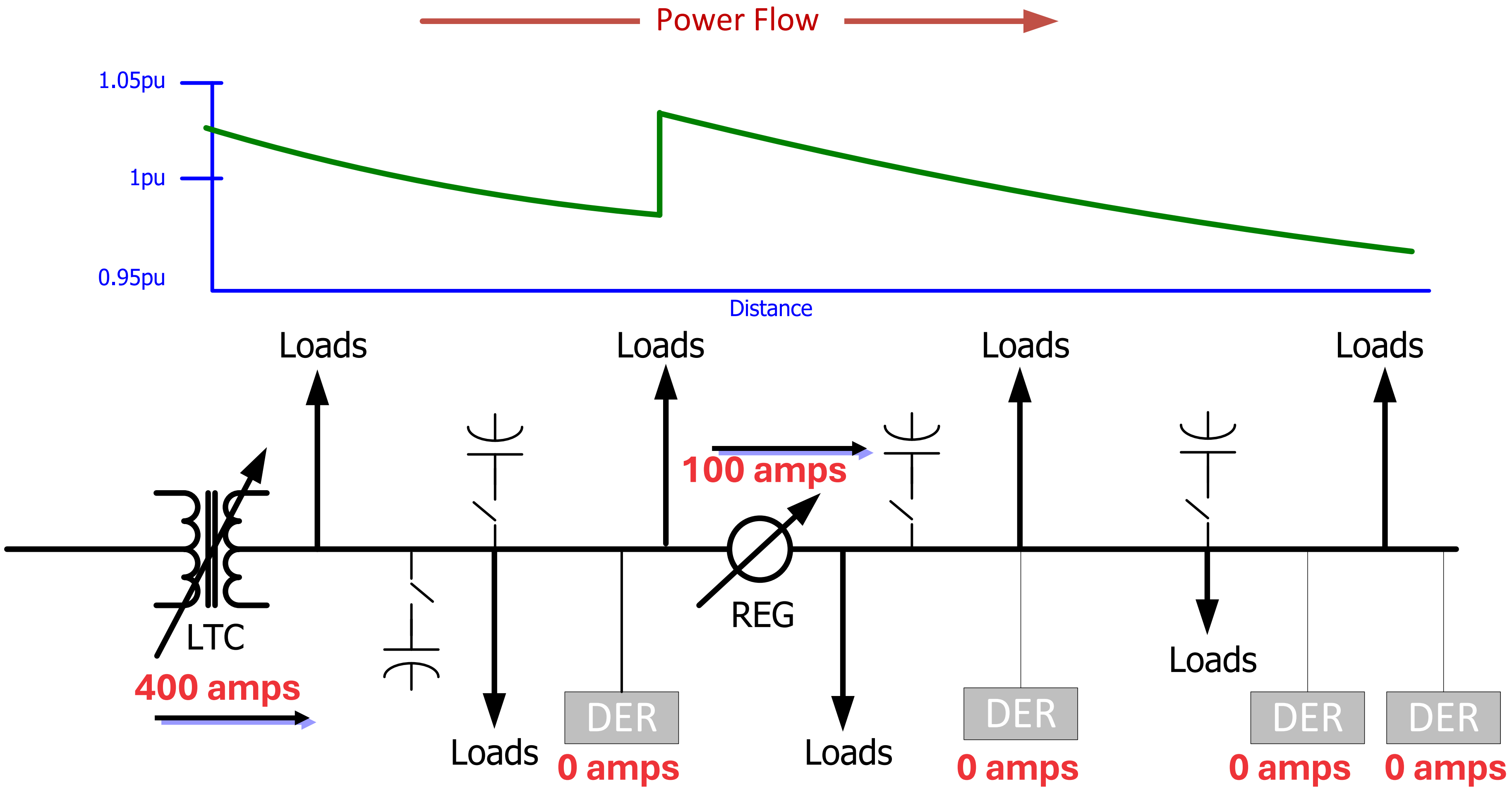
Basic Control Settings -LDC

Line Drop Compensation



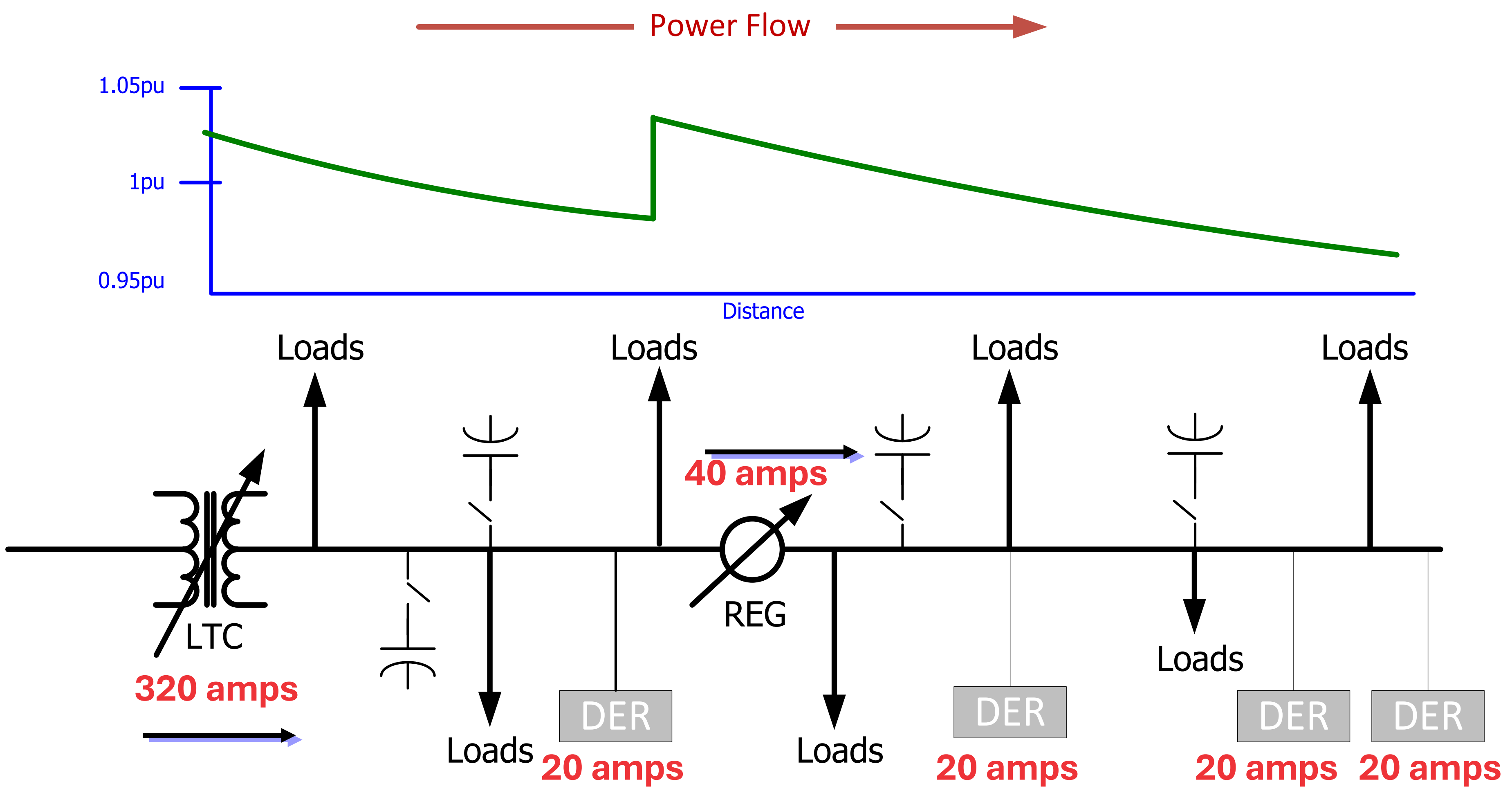
Basic Control Settings - LDC

Line Drop Compensation and DG - Evening with No DG Online



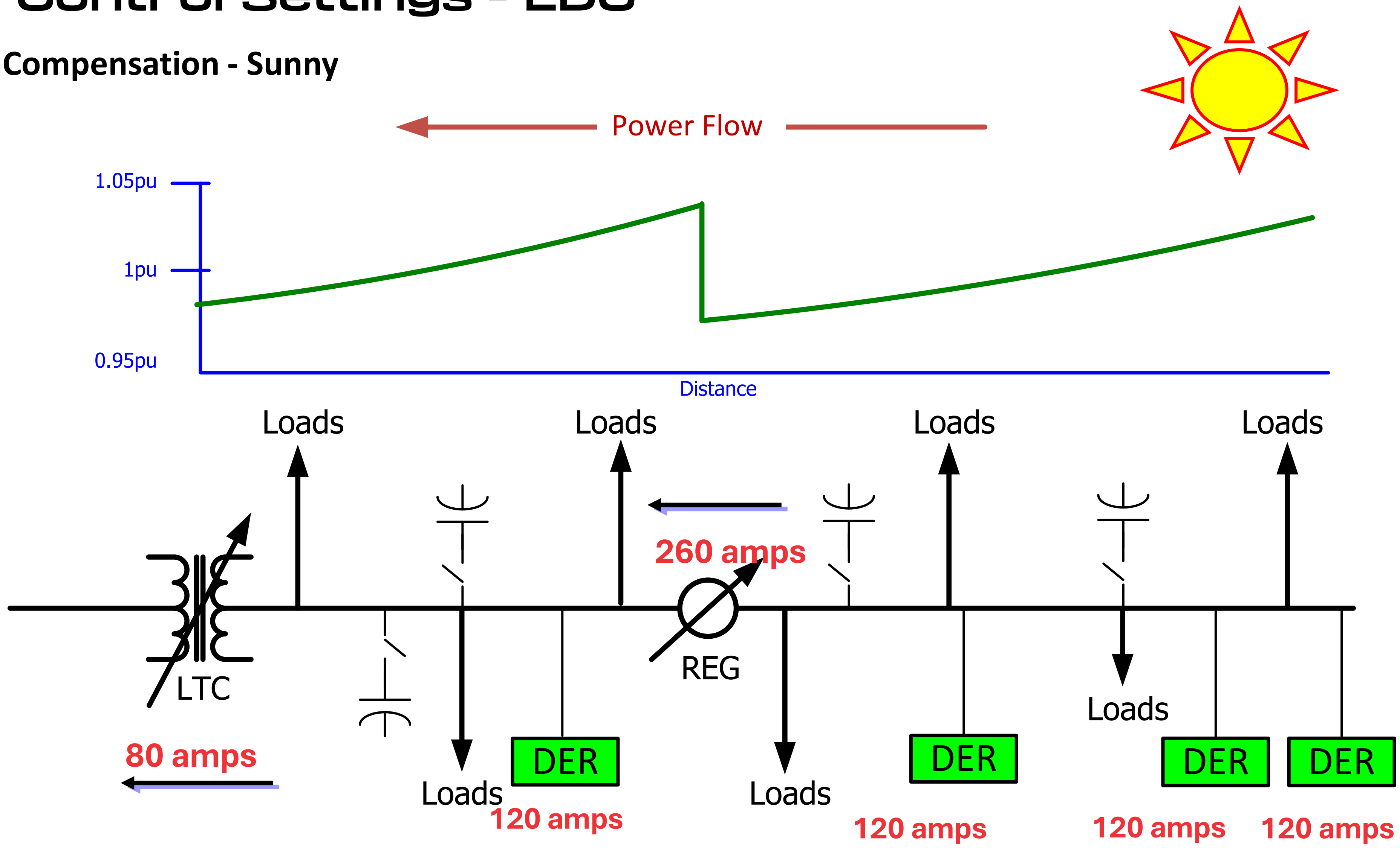
Basic Control Settings - LDC

Line Drop Compensation and DG - Partly Sunny



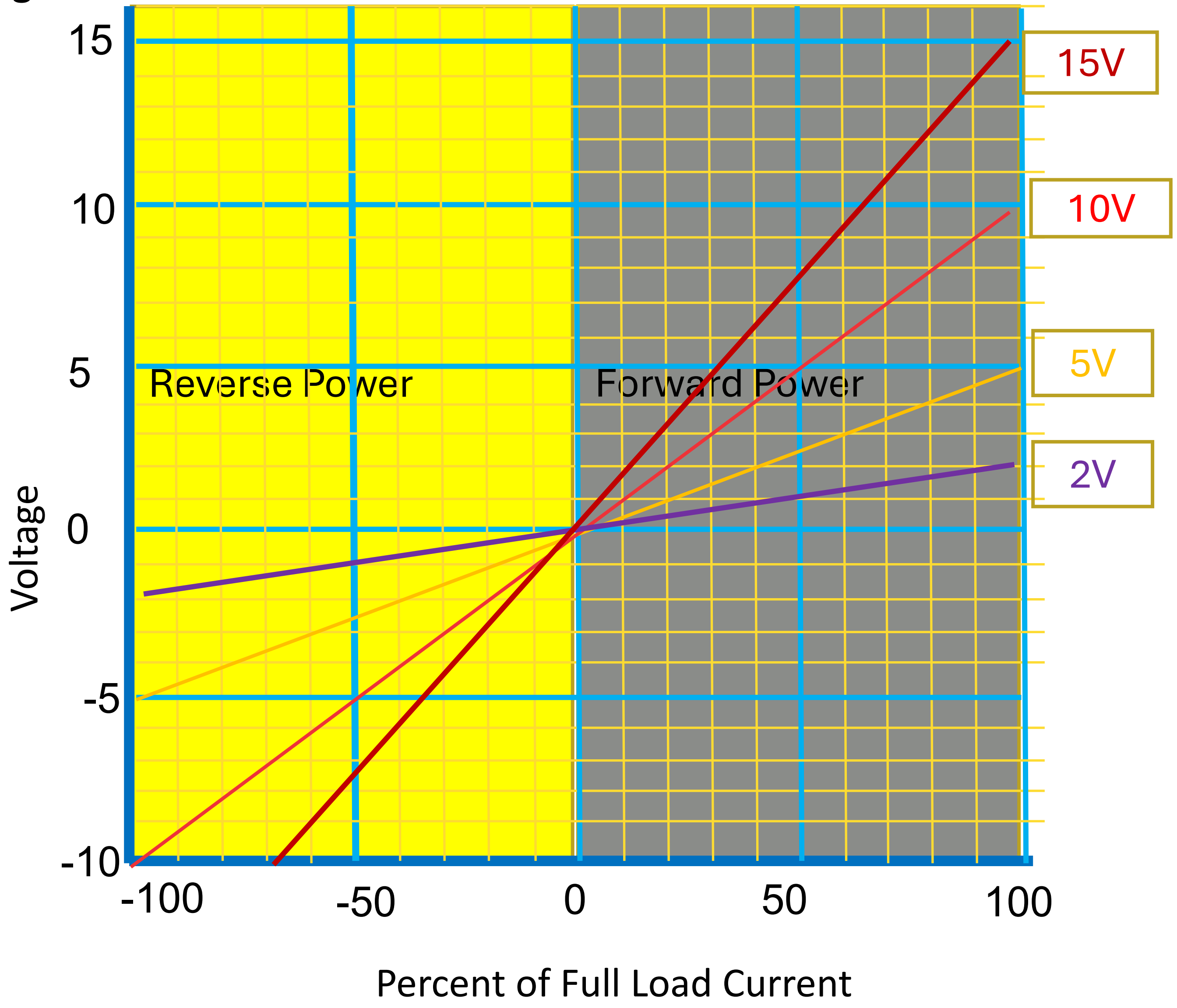
Basic Control Settings - LDC

Line Rise Compensation - Sunny



Basic Control Settings - LDC

LDC voltage vs load current – with Reverse Power



Notice that if the current is in reverse direction, the voltage is dropped instead of raised. The block lower voltage setting will limit low voltage in reverse direction due to line drop compensation.

Basic Control Settings - Blocks

Blocking

Two types of blocks:

1. Block only:
    1. Overcurrent blocking.
    2. Undervoltage blocking.
    3. Overvoltage blocking.
    4. Tap position.
    5. Reverse power.
    6. Comm block.
    7. Cooper Motor Seal-In switch.
    8. Low current block.
2. Runback:
    1. Overvoltage runback.

Basic Control Settings - Blocks

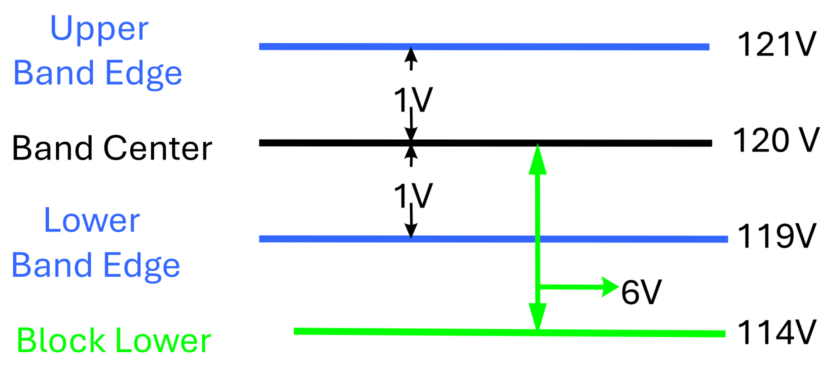
Blocking – Current Limit

1. Controller only rated for 200 ma.
2. When load current exceeds preset limits, controls are blocked.
3. Set via the LineLimit Current Setpoint.
4. Can be configured to Alarm.
5. Blocks both raise and lower for both automatic and remote.
6. Used for line regulators that may be tied to pick up addition load during switching/emergencies that cause the regulator to be overloaded.

Basic Control Settings - Blocks

Blocking – Undervoltage Block:

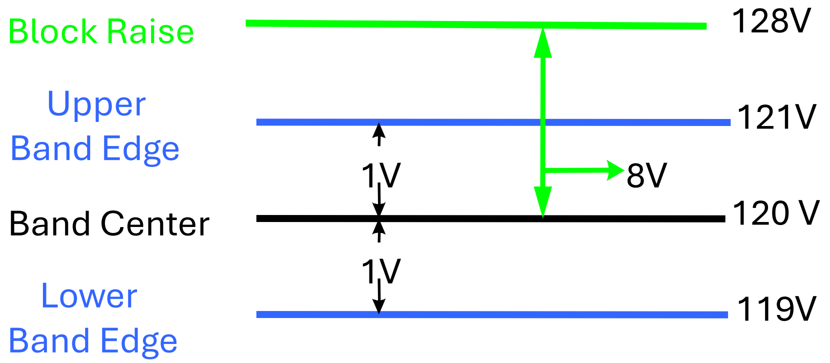
1. Used to keep voltage from dropping to low which could cause motors to stall.
2. If voltage falls below this level, voltage reduction is blocked and all Lower commands are blocked.
3. Can be configured from 95.0 – 135.0 Vac in 0.1 Vac increments.
4. Blocks lower in automatic and remote.
5. Can be configured to Alarm.



Basic Control Settings - Blocks

Blocking – Block Raise:

1. Used to keep voltage from going to high.
2. If voltage goes above this level, all Raise commands are blocked.
3. Can be configured from 95.0 – 135.0 V.ac in 0.1 V.ac increments.
4. Blocks lower in automatic and remote.
5. Can be configured to Alarm.
6. Supervised LDC.

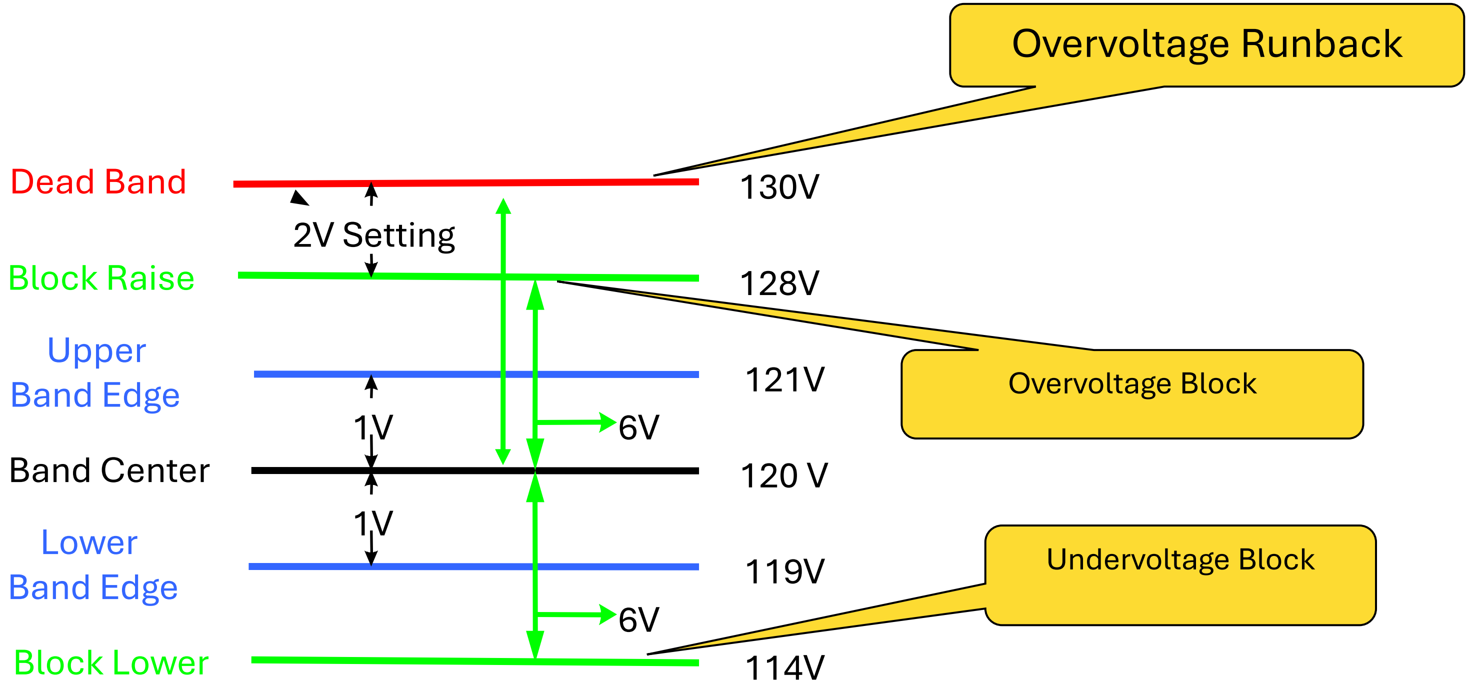


Basic Control Settings – Blocks First House Protection

Blocking – Force Lower

Overvoltage Runback – Block Raise

1. If voltage exceeds this level, Raise commands are blocked and Lower commands are issued until voltage goes below this level.
2. Lower commands will be issued immediately without time delay.



Regulator Controls Block on Tap (Load Bonus)

Blocking – Tap Position

1. Requires the tap position to be monitored using Keep Track (Regulator Internal).
2. Control allows different settings for the block on the lower and the block on the raise.
3. Incorrect tap position will cause undesirable blocking.
4. Can be used to generate alarms.
5. Will block automatic and remote.
6. Used with line regulators to limit tap range when adding additional load due to switching.

Basic Control Settings – Blocks on Tap

1. Limiting the regulation range increases the current carrying capabilities of the regulator

Table 8–Supplementary continuous-current ratings for single-phase regulators

Range of voltage regulation (%)	Continuous-current rating (%)
10.0	100
8.75	110
7.5	120
6.25	135
5.0	160

Table 9–Supplementary continuous-current ratings for three-phase regulators

Range of voltage regulation (%)	Continuous-current rating (%)
10.0	100
8.75	108
7.5	115
6.25	120
5.0	130

Nameplate Data to Locate – Siemens Regulators

1) PT Ratio
2) CT Ratio
3) Any Voltage Correction Factor
4) Regulator Type
5) Load Rating with Tap Block

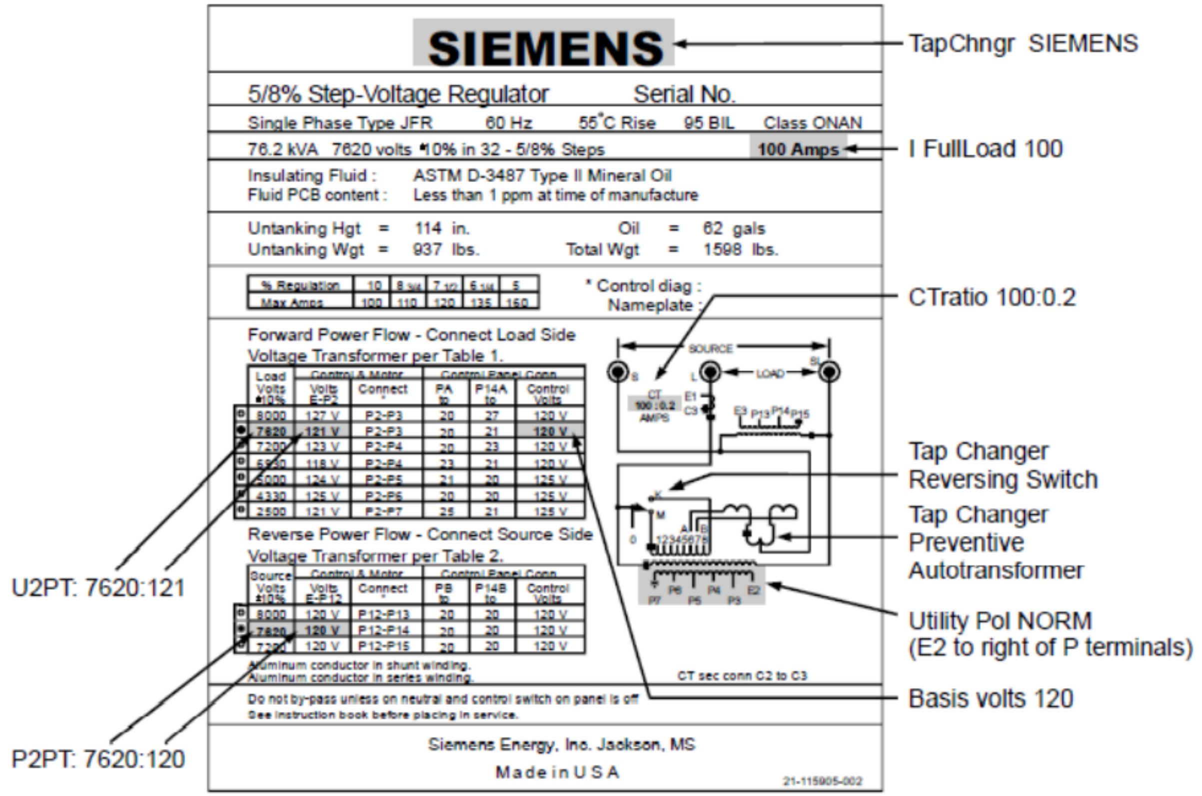
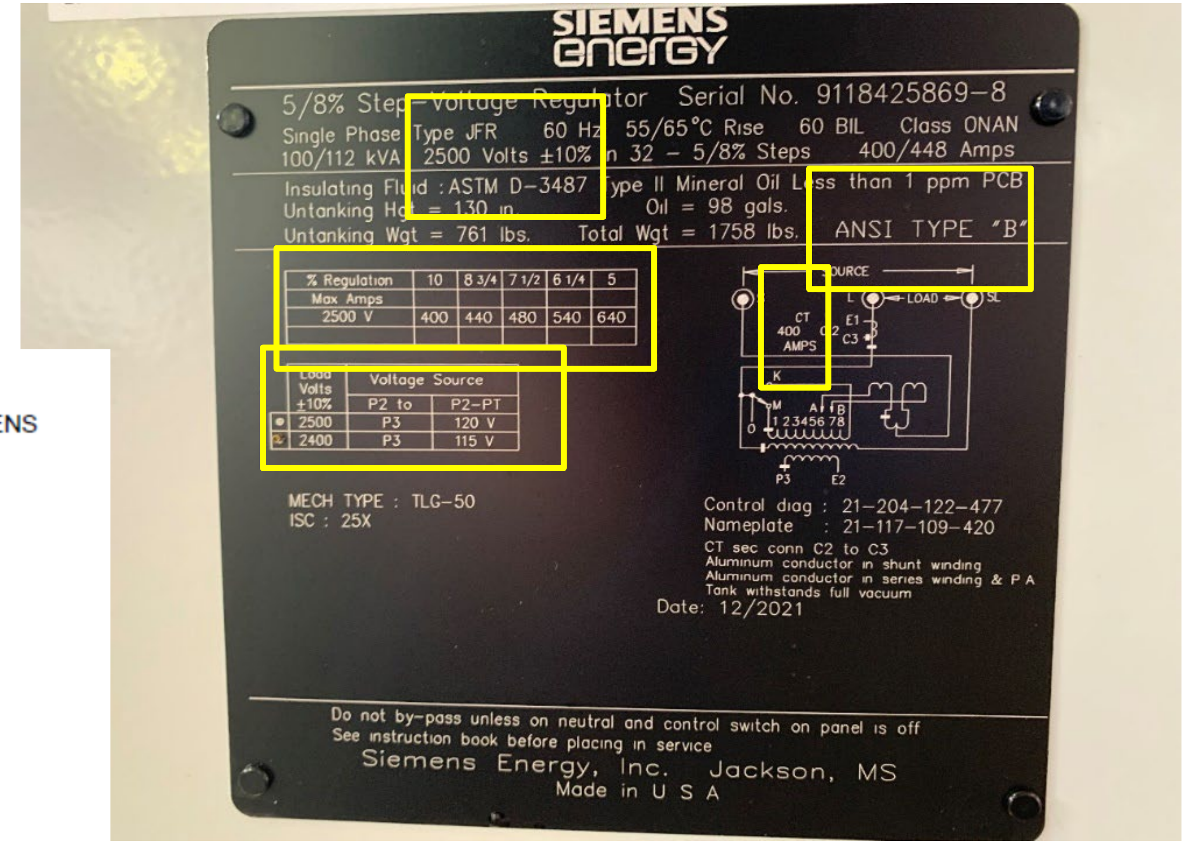
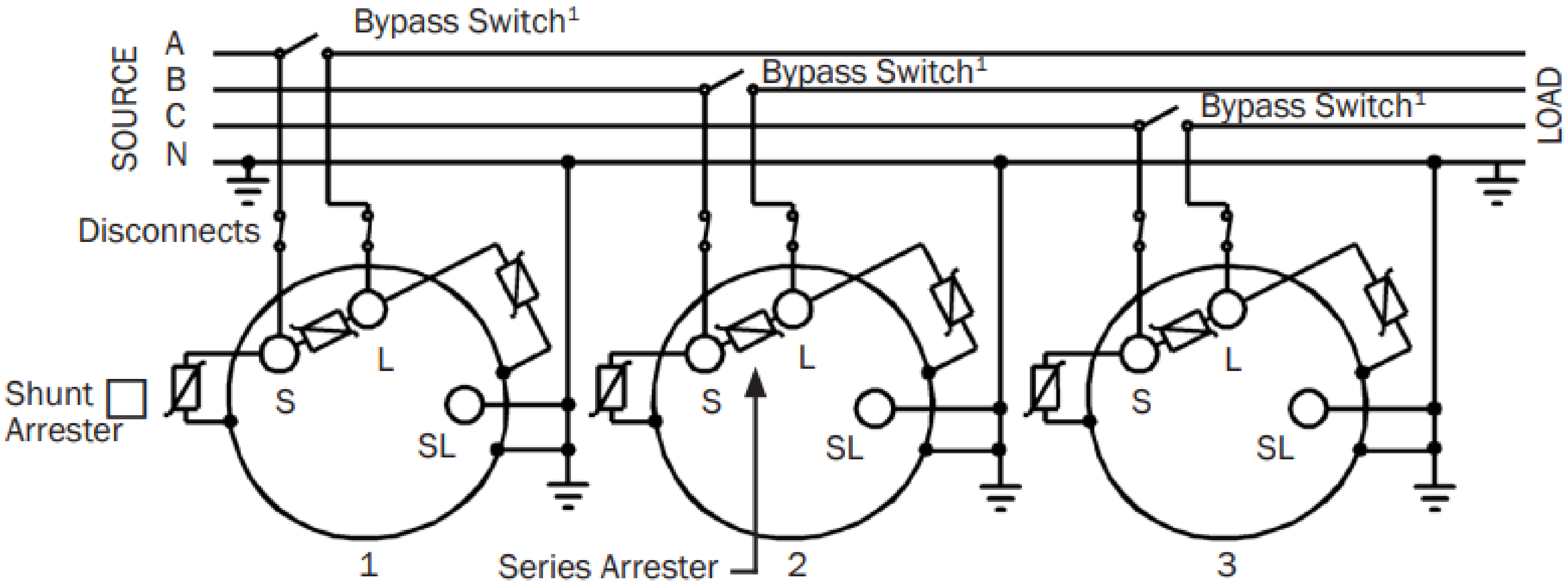


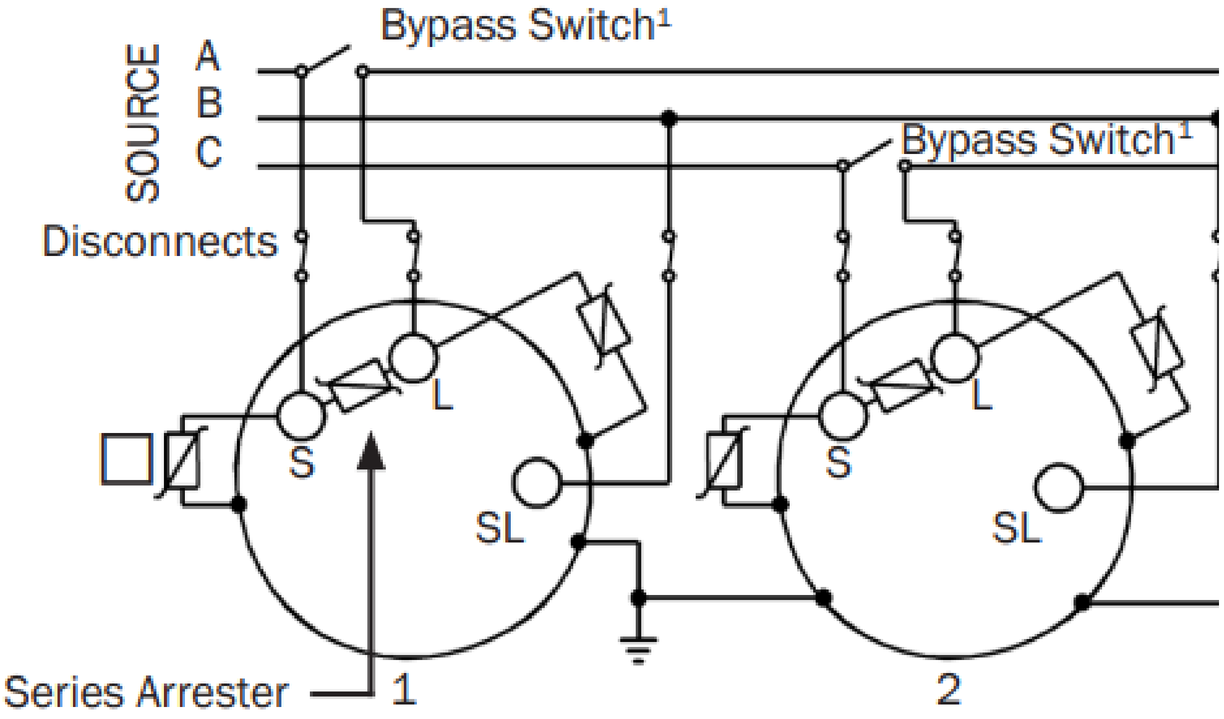
Figure 4.1 Typical Siemens Regulator Nameplate for older ANSI Type B (Inverted) Regulator
Note: Items are not highlighted on actual nameplate

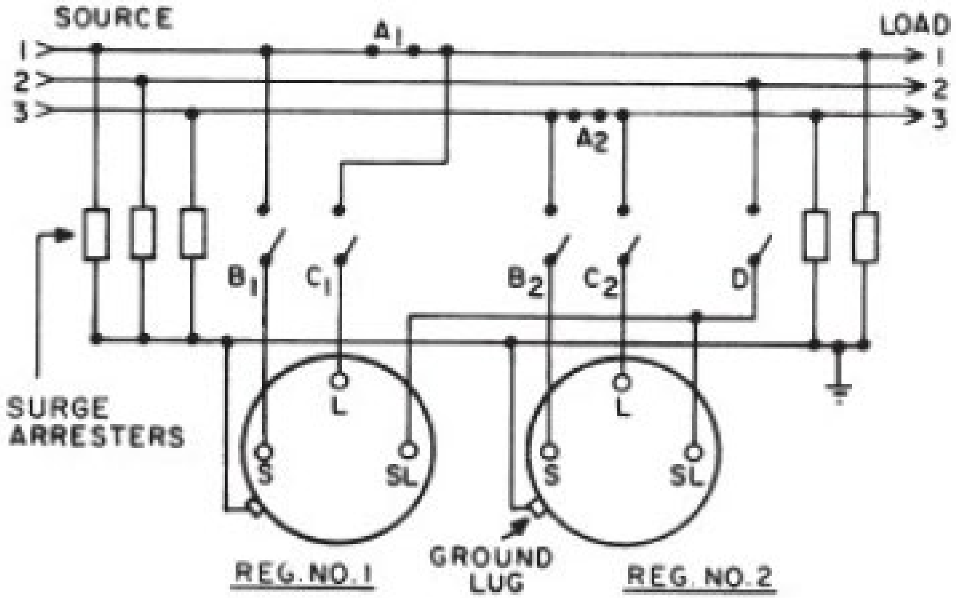


Three Phase Wye Grounded 4-Wire Connection



Open-Delta Connection





PHASE ROTATION	REG NO.	PHASE
1 - 2 - 3	1	LAG
	2	LEAD
3 - 2 - 1	1	LEAD
	2	LAG

Testing Open Delta for Lead and Lag

The LDC X Test

1. Place both regulators in manual and on the same tap.
2. Configure both controls to have same Bandcenter, Bandwidth and time delay.
3. Configure the R in both to 0 and the X in both to 10.
4. Place the controls in Auto.
5. After the finish tapping the regulator closest to 16R is the lagging regulator and the regulator closest to 16L is the leading regulator.

The Power Factor Test

1. Place both regulators in manual and on the same tap.
2. Configure both controls to have same Bandcenter, Bandwidth and time delay.
3. Configure the R in both to 0 and the X in both to 0.
4. Place the controls in Auto.
5. If the power factor is between 0.81 lag and 0.91 lead, then the lagging regulator will be raising the voltage and the leading regulator will be lowering the voltage.
6. If the power factor is below 0.81 lag, then both regulators will raise the voltage and the one at the higher voltage will be the lag.

Testing Open Delta for Lead and Lag

The Power Factor Test

1. For each regulator start with the phase angle set to 30 degrees and then record the power factor. Change it to 330 degrees and record the power factor. You will see on each regulator that one of the two power factors will look correct.

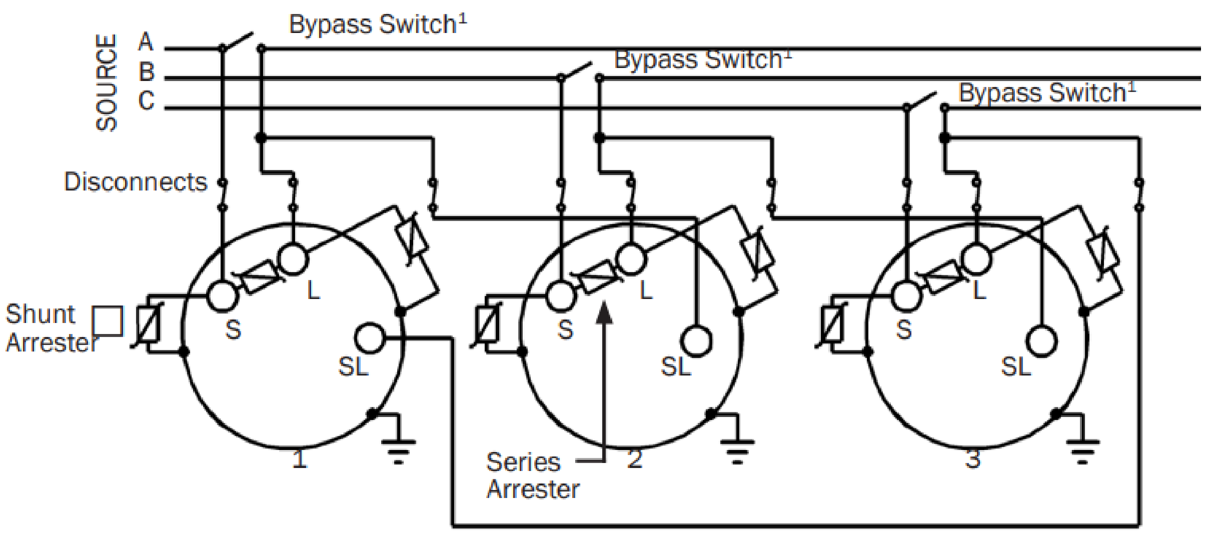
2. As an example:

		Lag	Lead
1.	Reg1	.91	-.77
2.	Reg2	.21	0.92

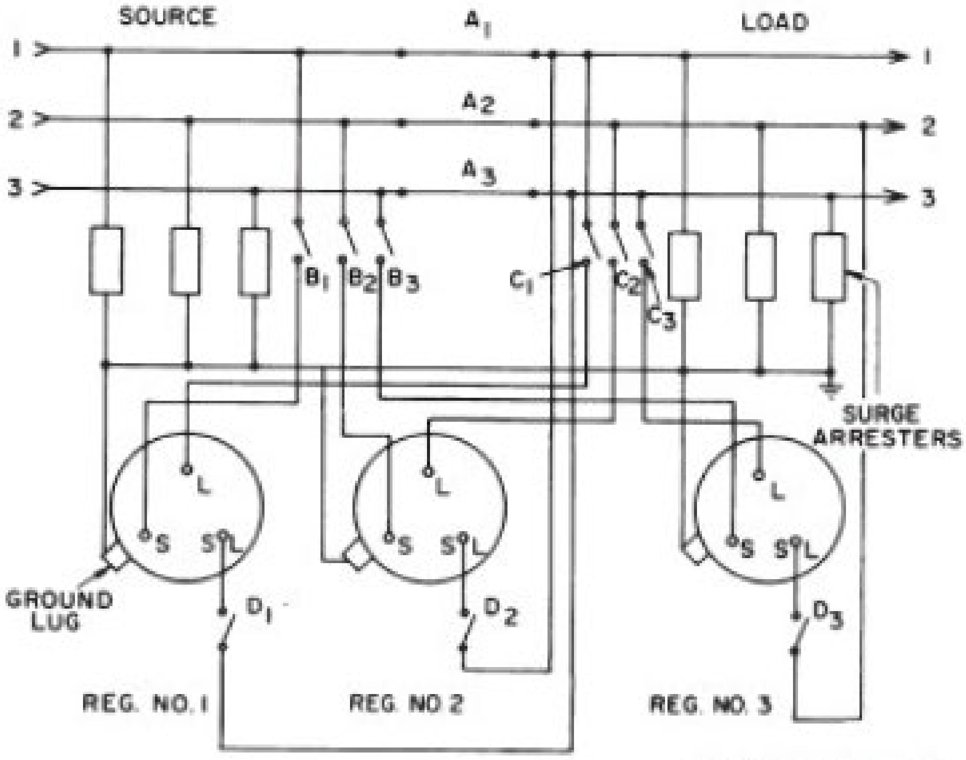
In this example, Reg 1 would be the lag regulator and Reg 2 would be the lead regulator.

Three Phase Closed Delta Connection

1. For closed delta all three regulators will either be lead or lag. Using the same power factor test and above for the open delta, one can determine whether they s



1- A-C 2- B-A 3- C-B



PHASE ROTATION	PHASE
1-2-3	LEAD
3-2-1	LAG

ANSI Regulator Types

Step-Voltage Regulators

A step-voltage regulator is "a voltage regulator in which the voltage and (or) phase angle of the regulated circuit are controlled in steps by means of taps without interrupting the load."4 There are two types of step-voltage regulators as defined by the ANSI:

(1) Type A, also known as "straight" design, and
(2) Type B, also known as "inverted" design.

ANSI Type A Regulator

C.2 Type A

Type A step-voltage regulators have the unregulated circuit voltage, V_{Source}, connected directly across the shunt (excitation) winding of the voltage regulator, as shown in Figure C.3. The series (tapped) winding is connected directly to the load side of the voltage regulator and, by adjusting taps, changes the regulated circuit voltage, V_{Load}. With Type A construction, the core excitation (flux) varies with the source voltage due to the fact the excitation winding is connected directly across the unregulated circuit. A separate voltage transformer assists in providing the regulated voltage supply for the control.

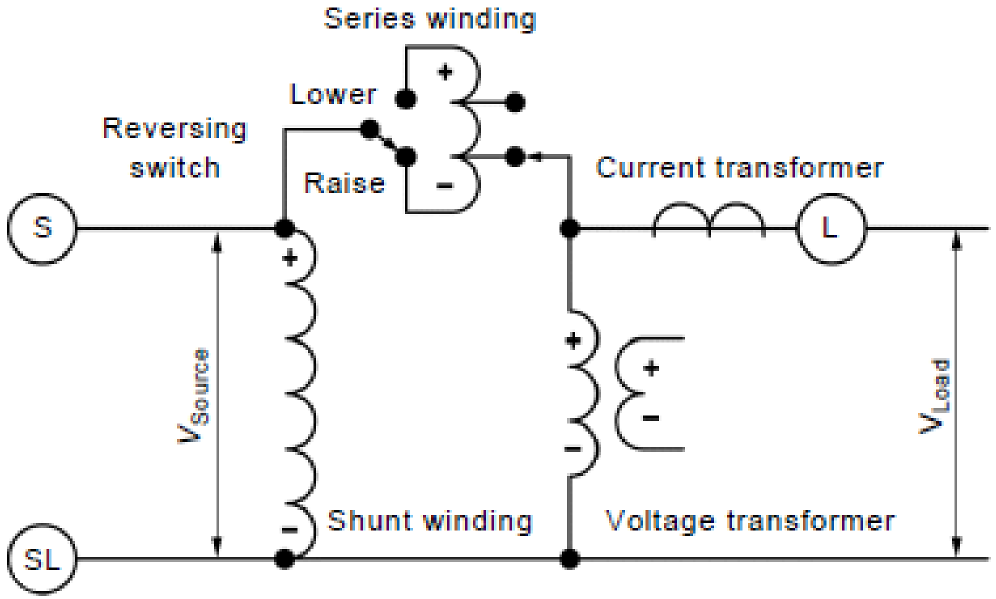


Figure C.3 – Type A

ANSI Type B Regulator

C.3 Type B

Type B step-voltage regulators are constructed with the unregulated circuit voltage, V_{Source}, applied by way of taps across the series winding and shunt (excitation) winding of the voltage regulator, as shown in Figure C.4. With Type B construction, the core excitation is essentially continuous, since the shunt (excitation) winding is connected directly with the voltage, V_{Load}, of the regulated circuit. A utility winding in the main coil is used in lieu of a separate voltage transformer providing the regulated voltage supply for the control.

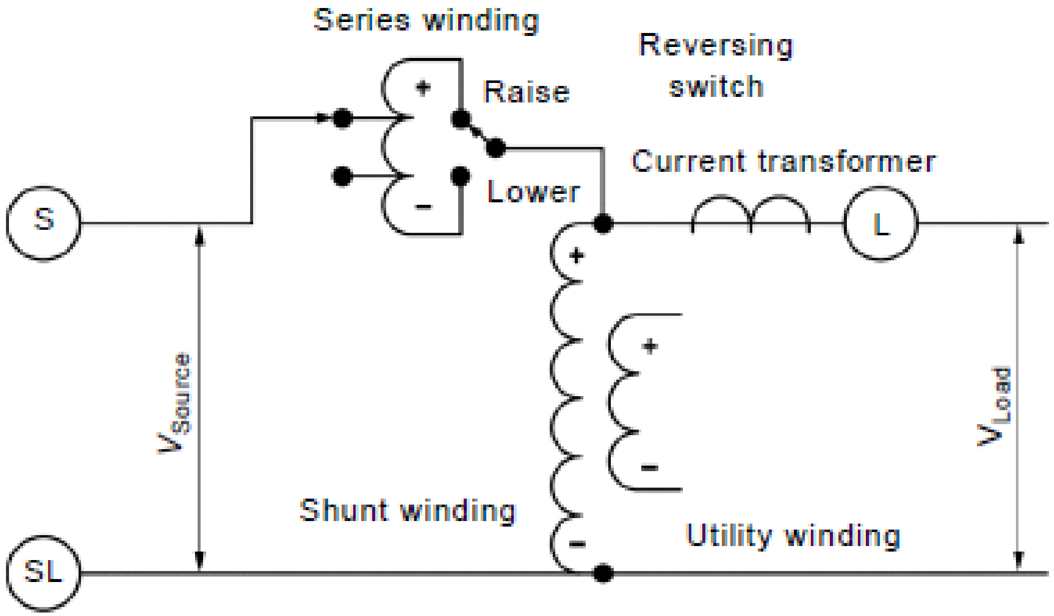
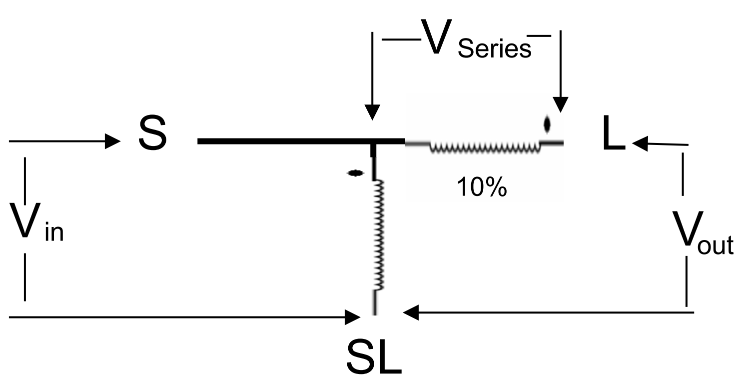


Figure C.4 – Type B

All Type A (Straight) Regulator

16 Raised



$V_{out} = V_{in} + V_{ser}$

$V_{ser} = 0.1\ V_{in}$

$V_{out} = V_{in} + 0.1\ V_{in}$

$V_{out} = 1.1\ V_{in}$

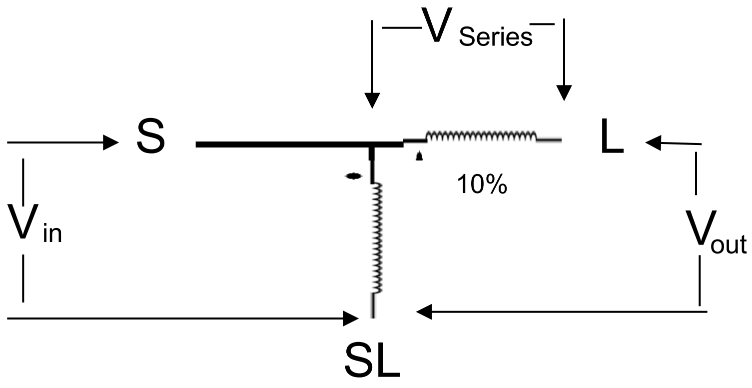
$\% \text{ Reg} = |(V_{out} – V_{in})|/V_{in}$

$= |(1.1V_{in} – V_{in})|/V_{in}$

$= 0.1/1$

$= 10\% = .75 \text{ V/tap}$

16 Lower



$V_{out} = V_{in} - V_{ser}$

$V_{ser} = 0.1\ V_{in}$

$V_{out} = V_{in} - 0.1\ V_{in}$

$V_{out} = 0.9\ V_{in}$

$\% \text{ Reg} = |(V_{out} – V_{in})|/V_{in}$

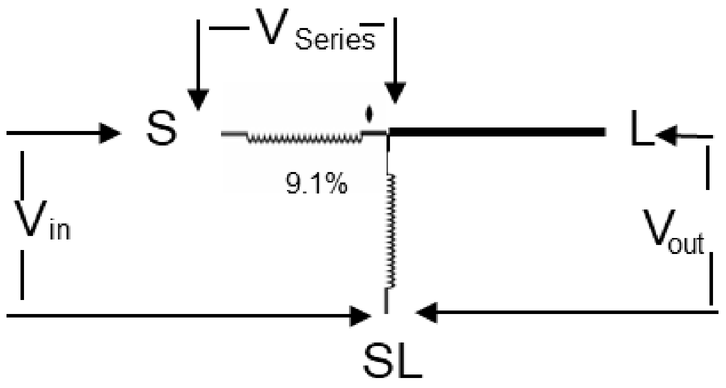
$= |(0.9V_{in} – V_{in})|/V_{in}$

$= 0.1/1$

$= 10\% = .75\text{V/tap}$

Cooper Regulator Inverted Design, ANSI type B

16 Raised



$V_{out} = V_{in} + V_{ser}$

$V_{ser} = 0.091\ V_{in}$

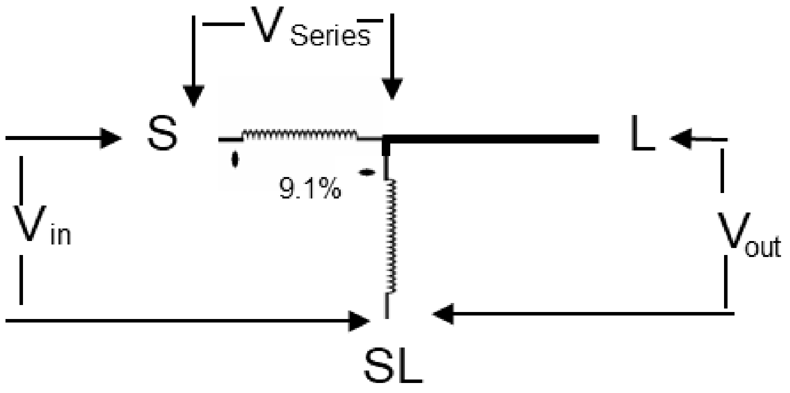
$V_{out} = V_{in} + 0.091\ V_{in}$

$V_{in} = V_{out} - 0.091\ V_{out}$

$V_{in} = 0.909\ V_{out}$

$$\begin{aligned}\%\ Reg &= |(V_{out} - V_{in})|/V_{in} \\ &= |(V_{out} - 0.909V_{out})|/0.909V_{in} \\ &= 0.091/0.909 \\ &= 10\% = .75V/tap\end{aligned}$$

16 Lower



$V_{out} = V_{in} - V_{ser}$

$V_{ser} = 0.091\ V_{in}$

$V_{out} = V_{in} - 0.091\ V_{in}$

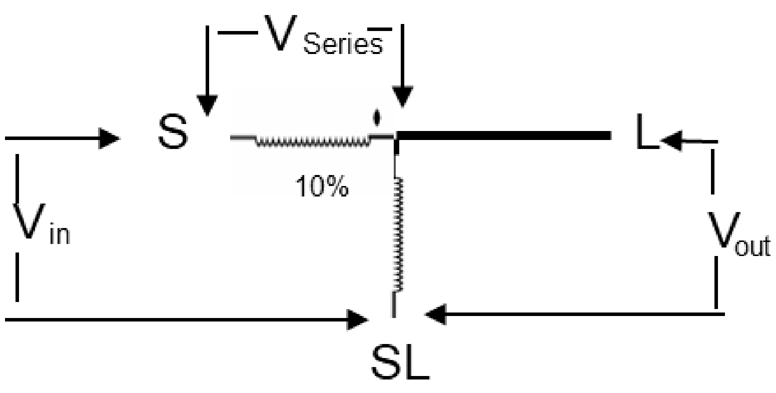
$V_{in} = V_{out} + 0.091\ V_{out}$

$V_{in} = 1.091\ V_{out}$

$$\begin{aligned}\%\ Reg &= |(V_{out} - V_{in})|/V_{in} \\ &= |(V_{out} - 1.091V_{out})|/1.091V_{in} \\ &= 0.091/1.091 \\ &= 8.34\% = .6255V/tap\end{aligned}$$

GE, Howard and Siemens Regulator Inverted Design, ANSI type B

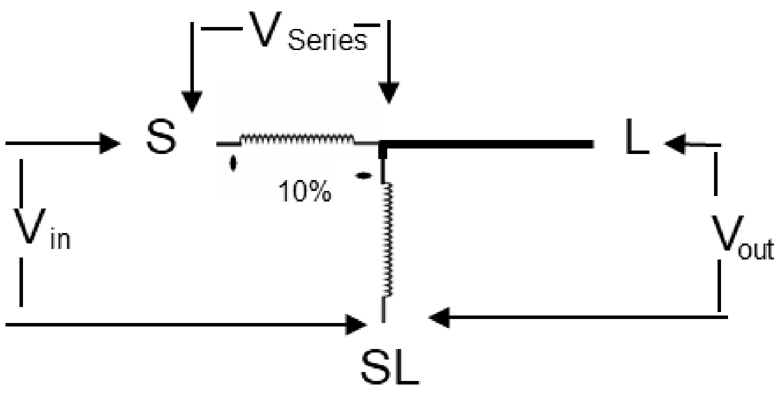
16 Raised



$V_{out} = V_{in} + V_{ser}$
$V_{ser} = 0.1\ V_{in}$
$V_{out} = V_{in} + 0.1\ V_{in}$
$V_{in} = V_{out} – 0.1\ V_{out}$
$V_{in} = 0.9\ V_{out}$

% Reg = $|(V_{out} – V_{in})|/V_{in}$
= $|(V_{out} – 0.9V_{out})|/0.9V_{in}$
= 0.1/0.9
= 11.11% = .83V/tap

16 Lower



$V_{out} = V_{in} - V_{ser}$
$V_{ser} = 0.1\ V_{in}$
$V_{out} = V_{in} - 0.1\ V_{in}$
$V_{in} = V_{out} + 0.1\ V_{out}$
$V_{in} = 1.1\ V_{out}$

% Reg = $|(V_{out} – V_{in})|/V_{in}$
= $|(V_{out} – 1.1V_{out})|/1.1V_{in}$
= 0.1/1.1
= 9.09% = .68V/tap

Typical Voltages per Tap

Tap	S/Ho/GE A	S/Ho/GE B	Cooper A	Cooper B
16	132.00	133.28	132.00	132.00
15	131.25	132.45	131.25	131.25
14	130.50	131.62	130.50	130.50
13	129.75	130.79	129.75	129.75
12	129.00	129.96	129.00	129.00
11	128.25	129.13	128.25	128.25
10	127.50	128.30	127.50	127.50
9	126.75	127.47	126.75	126.75
8	126.00	126.64	126.00	126.00
7	125.25	125.81	125.25	125.25
6	124.50	124.98	124.50	124.50
5	123.75	124.15	123.75	123.75
4	123.00	123.32	123.00	123.00
3	122.25	122.49	122.25	122.25
2	121.50	121.66	121.50	121.50
1	120.75	120.83	120.75	120.75
0	120.00	120.00	120.00	120.00
-1	119.25	119.32	119.25	119.37
-2	118.50	118.64	118.50	118.75
-3	117.75	117.96	117.75	118.12
-4	117.00	117.28	117.00	117.50
-5	116.25	116.60	116.25	116.87
-6	115.50	115.92	115.50	116.25
-7	114.75	115.24	114.75	115.62
-8	114.00	114.56	114.00	115.00
-9	113.25	113.88	113.25	114.37
-10	112.50	113.20	112.50	113.75
-11	111.75	112.52	111.75	113.12
-12	111.00	111.84	111.00	112.49
-13	110.25	111.16	110.25	111.87
-14	109.50	110.48	109.50	111.24
-15	108.75	109.80	108.75	110.62
-16	108.00	109.12	108.00	109.99

Typical Allowable Voltage Per Tap

Ratio Tolerances

GE Energy
Digital Energy
Shreveport LA

Type A Regulator Ratio Tolerances

Assume
1) 10.4% buck or boost 16L to 16R
2) (32) steps of 0.65% per step

Position	Min.	Norm.	Max.	Position	Min.	Norm.	Max.
16L	0.894	0.896	0.898	1R	1.004	1.006	1.008
15L	0.900	0.902	0.904	2R	1.011	1.013	1.015
14L	0.907	0.909	0.911	3R	1.017	1.019	1.021
13L	0.913	0.915	0.917	4R	1.024	1.026	1.028
12L	0.920	0.922	0.924	5R	1.030	1.032	1.034
11L	0.926	0.928	0.930	6R	1.037	1.039	1.041
10L	0.933	0.935	0.937	7R	1.043	1.045	1.047
9L	0.939	0.941	0.943	8R	1.050	1.052	1.054
8L	0.946	0.948	0.950	9R	1.056	1.058	1.060
7L	0.952	0.954	0.956	10R	1.063	1.065	1.067
6L	0.959	0.961	0.963	11R	1.069	1.071	1.073
5L	0.965	0.967	0.969	12R	1.076	1.078	1.080
4L	0.972	0.974	0.976	13R	1.082	1.084	1.086
3L	0.978	0.980	0.982	14R	1.089	1.091	1.093
2L	0.985	0.987	0.989	15R	1.095	1.097	1.099
1L	0.991	0.993	0.995	16R	1.102	1.104	1.106
0	0.998	1.000	1.002				

Type B Regulator Ratio Tolerances

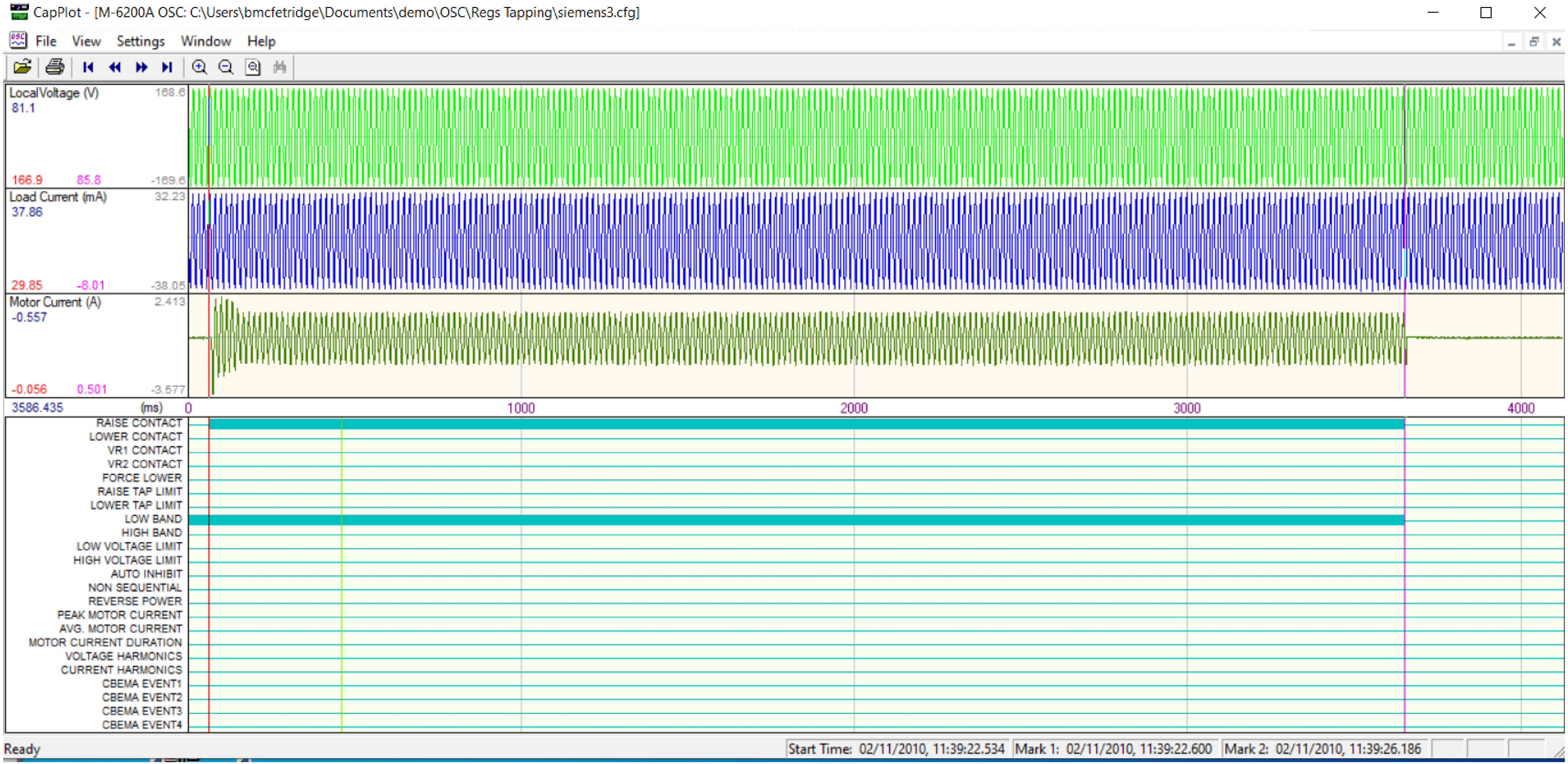
GE Energy
Digital Energy
Shreveport LA

Type B Regulator Ratio Tolerances

Assume
1) 9.4% buck or 10.4% boost 16L to 16R

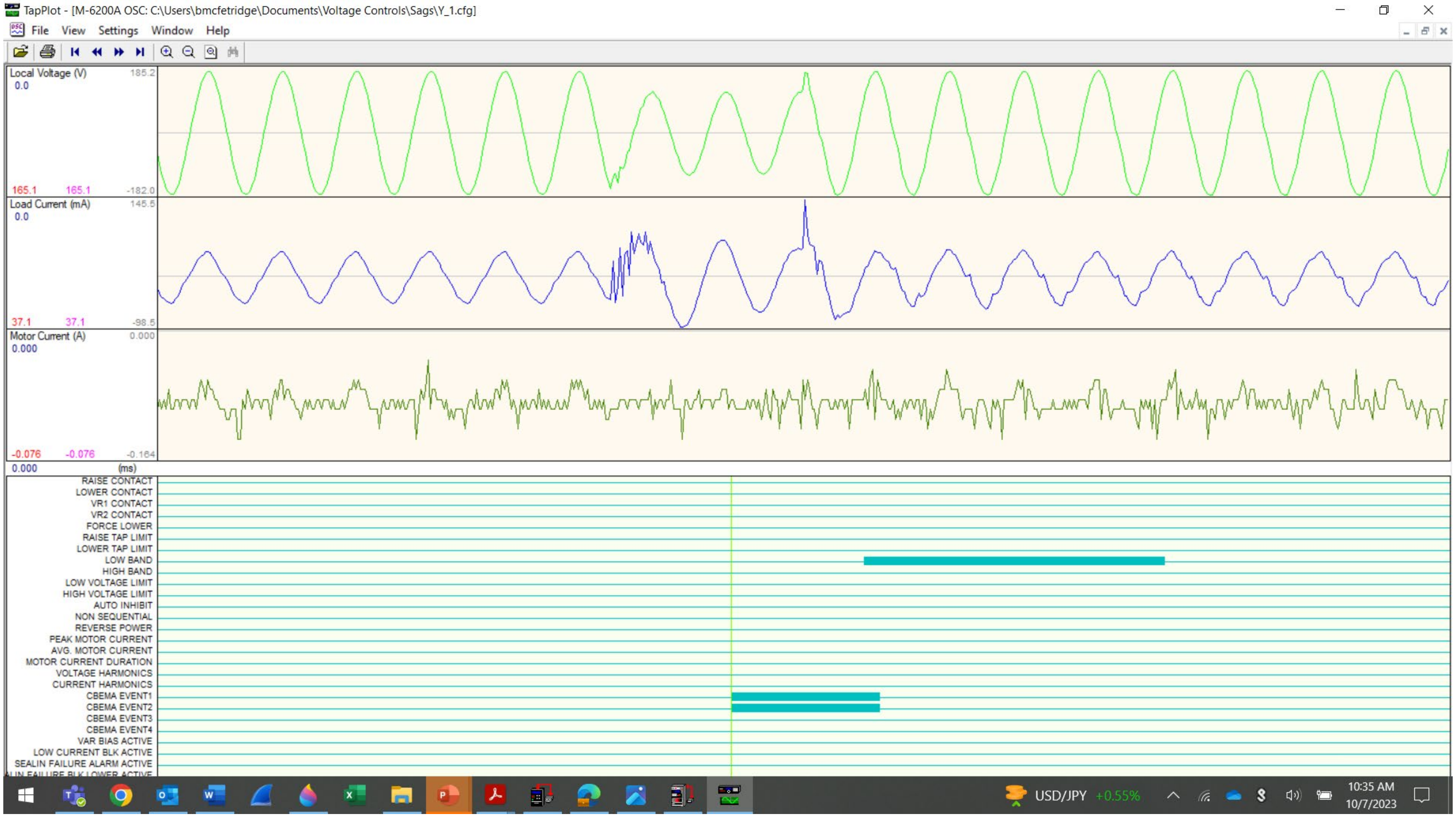
Position	Min.	Norm.	Max.	Position	Min.	Norm.	Max.
16L	0.902	0.906	0.911	1R	1.000	1.005	1.010
15L	0.907	0.911	0.916	2R	1.007	1.012	1.017
14L	0.912	0.917	0.922	3R	1.013	1.018	1.023
13L	0.918	0.922	0.927	4R	1.020	1.025	1.030
12L	0.923	0.928	0.933	5R	1.027	1.032	1.037
11L	0.929	0.934	0.938	6R	1.034	1.039	1.044
10L	0.935	0.939	0.944	7R	1.041	1.046	1.051
9L	0.940	0.945	0.950	8R	1.048	1.053	1.059
8L	0.946	0.951	0.956	9R	1.055	1.060	1.066
7L	0.952	0.957	0.962	10R	1.062	1.068	1.073
6L	0.958	0.963	0.968	11R	1.075	1.070	1.080
5L	0.964	0.969	0.974	12R	1.077	1.083	1.088
4L	0.970	0.975	0.980	13R	1.085	1.090	1.096
3L	0.976	0.981	0.986	14R	1.093	1.098	1.104
2L	0.983	0.988	0.992	15R	1.100	1.106	1.111
1L	0.988	0.993	0.998	16R	1.109	1.114	1.120
0	0.995	1.000	1.005				

Siemens Regulating Issuing a Raise



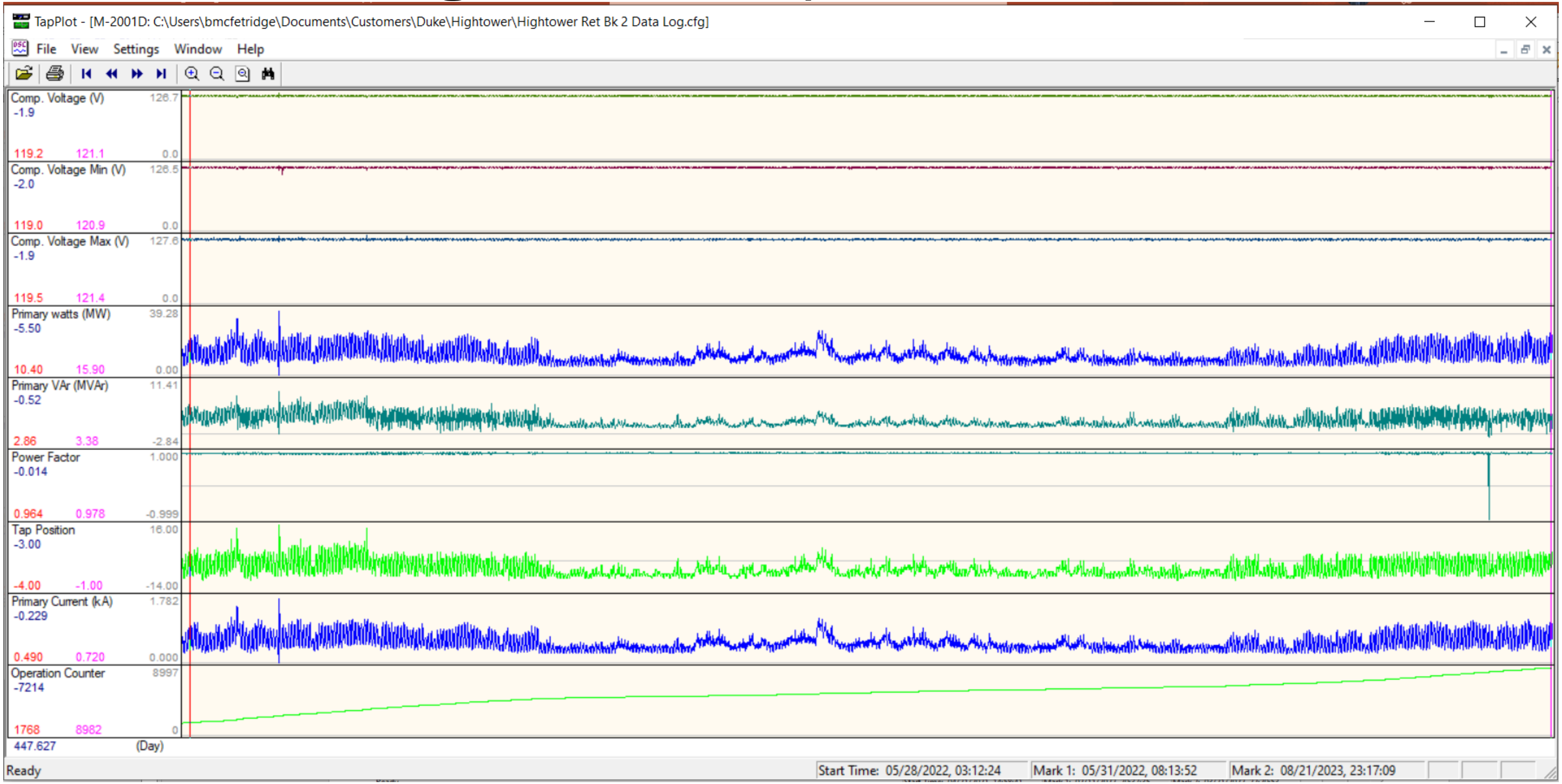
Regulator causing flicker due to worn tap

Motor start cause sag

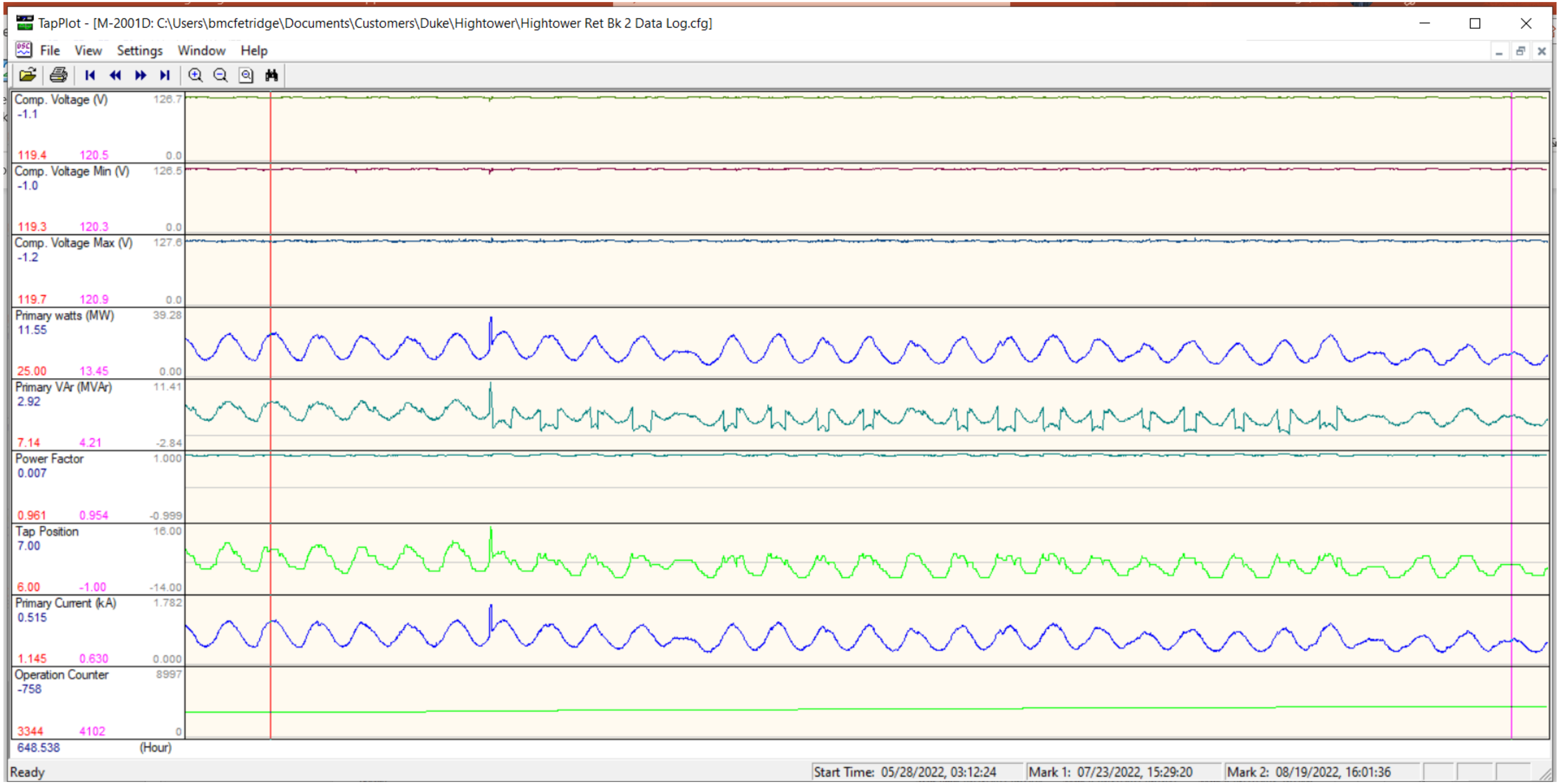


Controller capturing harmonics

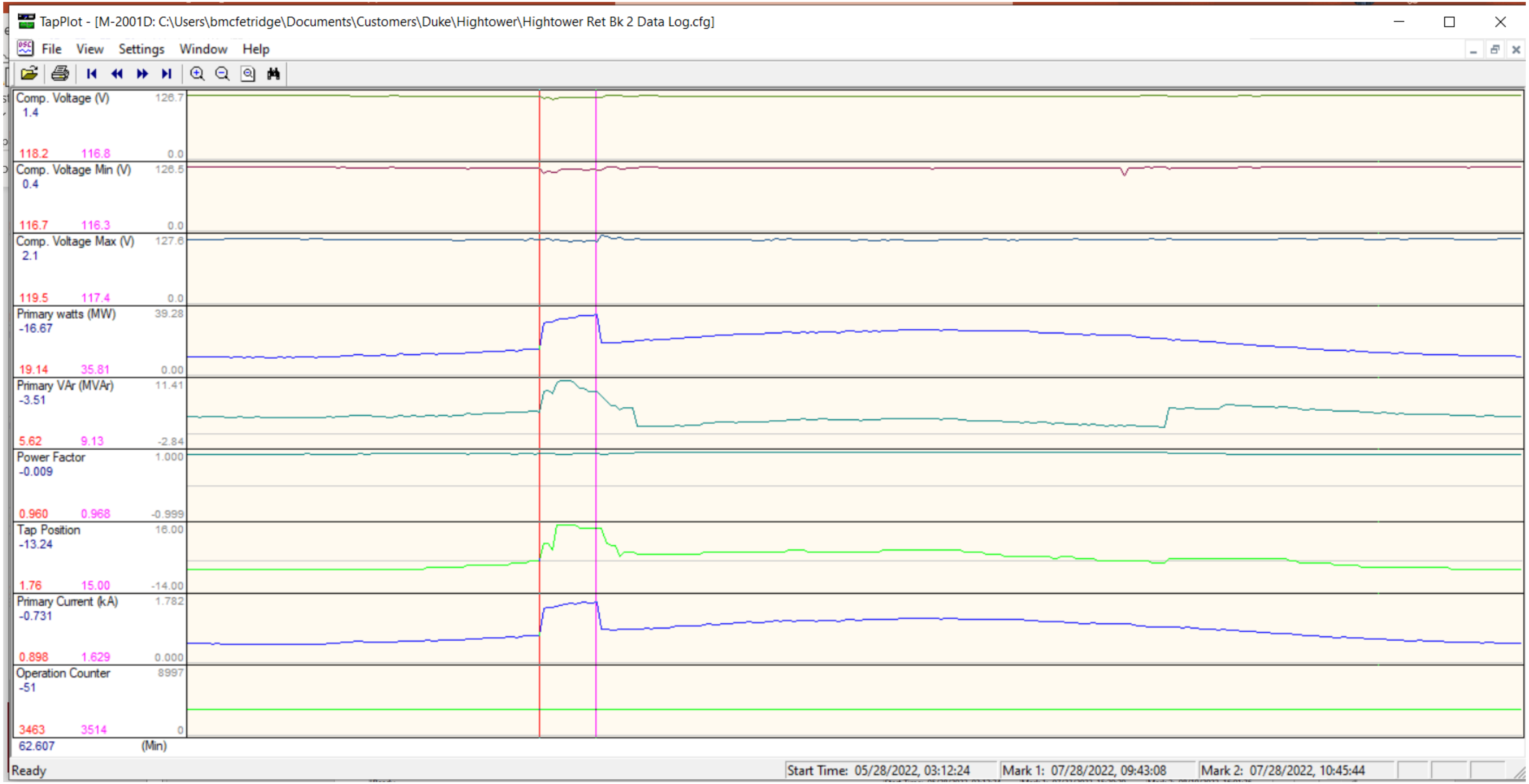
Controller Dat Log 5 Minute Samples



Controller Dat Log 5 Minute Samples – Drilling Down



Controller Dat Log 5 Minute Samples – Drilling Down



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